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The influence of air humidity on human heat stress in a hot environment

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This article aims to present the physical adaptation capabilities of a human, seen as a response to extreme hot and dry or hot and humid conditions. Adaptation capabilities are expressed as safe exposure time in two variants: at rest and during physical activity. The study shows the results of calculations of the variability over time of the core temperature and skin temperature as well as heat balance. Calculations were made according to Standard No. EN ISO 7933:2005 on the basis of assumed and actual meteorological data. The results of the calculations show that in these conditions a hot but dry environment enables a human (although to a limited extent) to stay and perform low physical activity, provided access to drinking water is ensured. In contrast, a hot but humid environment causes more serious problems, due to the inability to reduce skin temperature by evaporation of sweat from the skin surface.

Keywords: heat stress; heat balance; hot environment; air humidity; partial pressure of water vapor; predicted heat strain

1. Introduction – human heat balance

The ‘heat’ sensation forms part of the range of human subjective feelings that may be attributed to a variety of reasons. High air temperature does not necessarily have to be its direct cause because a heat sensation may be caused by extreme physical effort in a low ambient temperature, the same thermal sensation that is generated by strong emotions or a health condition caused by an infection. From a physiological point of view, the ‘warm’ or ‘hot’ sensation is associated with body heat accumulation, expressed in joules, which is accompanied by an increase in human body temperature.

This sensation takes place when the rate of heat generated in the human body exceeds the rate of its reception by the environment. Every living warm-blooded organism of a mammal or a bird strives to maintain a thermal balance with the environment to maintain a relatively stable core temperature (about 37 °C in humans) that keeps the optimal course of physiological processes taking place in the body and to protect the brain from overheating. The human body can tolerate small deviations in the range of ±1 °C without any adverse health consequences. Such deviations are, however, reflected in the subjective perception of the surrounding thermal environment [1–3].

In general, three causes of heat accumulation in the body can be distinguished. Heat is accumulated when:

(1) the rate of energy produced in the body (the metabolic rate) is so fast that the environment is unable to take up all of the heat generated at one time (endogenous heat load);
(2) the ambient temperature t_a and/or the radiation temperature t_r outnumber the average skin surface temperature t_{sk} (exogenous heat load);
(3) the factors listed in (1) and (2) occur simultaneously.

Metabolic heat (endogenous heat load) can be dissipated to the environment on condition that several thermoregulation mechanisms have been started. Effectiveness of such mechanisms depends on the environmental conditions that are determined by t_a (°C), t_r (°C), relative air humidity (RH, %) and air velocity (V, m/s).

The process of heat exchange between the human body and the environment is described by the conceptual equation of thermal balance [1,2,4]:

$$M = W \pm R \pm C \pm E \pm RES + \Delta S,$$

where M = density of the metabolic power flux of heat production (W/m^2); W = density of the power flow used for work (power load) (W/m^2); $(R + C)$ = density of power flux lost due to radiation and convection (W/m^2); E = density of the power flux lost as a result of evaporation of sweat (W/m^2); RES = density of the power stream lost as a result of breathing (W/m^2); ΔS = accumulation of heat (W/m^2).

Subjective assessment of a hot environment and its gradation, e.g., slightly warm, warm or hot, depends on the amount of thermal energy ΔS accumulated in the body. Under given environmental conditions of a hot

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environment, the greater the mass of a human being, the smaller the effect of heat accumulation occurring per unit of time on the increase of the temperature of his body. The relationship $\Delta S \approx 300$–$350\,\mathrm{kJ}$ is considered a health-safe level for heat accumulation in a 80-kg human body. This translates into an increase in body temperature of about 1.0–1.3 °C

All components of the heat balance equation are expressed in watts per square meter. The reason for this is twofold: heat transfer takes place through the human skin surface and the process takes place over time. In order to obtain the value of ΔS measured in joules, it is necessary to multiply the value expressed in watts per square meter by the human body surface area in square meters and the exposure time, expressed in seconds. The '$\pm$' sign indicates that the heat from the body can be not only dispersed into the environment, but also taken up by the body from the environment.

In a hot climate, it is desirable for a human body to effectively transfer excess heat to the environment. Given a wide variety of thermoregulatory mechanisms included in the heat balance equation, the living organisms have sufficient room for maneuver and can use heat transfer mechanisms in various situations. The body defends itself against harmful heat accumulation by trying to release its excess to the external environment. If the conditions are favorable and the skin surface temperature (t_{sk}) exceeds the air temperature (t_a) and the radiation temperature (t_r), heat energy can be transferred outside via convection and radiation. Sweating begins when air temperature exceeds 28–32 °C (or during a significant physical effort regardless of the ambient temperature) [1–4].

In a hot environment, body heat is mainly lost through evaporation. The effectiveness of this process depends on the vapor pressure contained in the air, i.e., indirectly on the relative humidity and air temperature. In particularly unfavorable conditions of a hot and humid environment, evaporation is limited or may not occur at all, despite the intense secretion of sweat from the body. The content of water vapor in a hot environment is essential for the exchange of heat between the human body and the environment.

To assess the thermal load of the human in a hot environment (also in the mining industry), the wet bulb globe temperature (WBGT) index is used [5,6]. More precise is the predicted heat strain (PHS) model which has been developed along with Standard No. EN ISO 7933:2005 [4].

The algorithms described in EN ISO 7933:2005 annex were validated on a data base including 747 laboratory experiments and 366 field experiments from eight research laboratories lead by Malchaire [7–9]. Table 1 presents the ranges of conditions for which the PHS model can be considered validated.

Table 1. Ranges of validity of the predicted heat strain model [4].

Parameter	Range
t_a (°C)	15–50
p_a (kPa)	0–4.5
V (m/s)	0–3
M (W)	100–450
I_{cl} (clo)	0.1–1.0

Note: I_{cl} = thermal insulation of clothing; M = metabolic rate; p_a = partial pressure of water vapor; t_a = air temperature; V = air velocity.

The PHS program allows for tracking the response of the human body to individual physical parameters of a hot environment. Its aim is to assess thermal loads affecting a human working in a hot environment, and in particular to simulate thermal loads.

The assessment, according to the PHS program, is based on the thermal balance and predicted values of physiological variables resulting from calculations, which determine the state of a human body after the lapse of a specific amount of time. The following parameters are of crucial importance for the thermal load assessment: core temperature (t_{cr}), the expected acceptable exposure time, equivalent to the time needed to reach the temperature of $t_{cr} = t_{re} = 38$ °C in the core (cr) or rectum (re) considered to be a safe health exposure time, and mass of secreted sweat. Calculations are based on the dataset containing information on physical parameters of the environment where work is to be performed and on the metric parameters of the employee to perform such work, including the height and mass of the body, the metabolic rate and physical work (power load), thermal insulation of the clothing used, etc.

It is assumed that physiological parameters of a person who is to start work are set at the rest level, including the body temperature t_{cr} at about 37 °C and the mean skin surface temperature t_{sk} at about 34 °C. The results from the calculations illustrate the variability of the selected physiological parameters as a function of time influenced by various combinations of changing safe values of microclimate parameters, the metabolic rate or clothing used. The PHS program used for computational simulation in this article was created as part of the RESCLO project (in which the aim of the study was the problem of thermal load of mine rescuers) based on the assumptions of Standard No. EN ISO 7933:2005 and the authors' own research [10].

The purpose of this article was to show how the air humidity modifies the time of performing work in a hot environment. The calculation simulations of thermal balance (PHS model) are presented on the basis not only of the selected condition (which showed a direction of the change) but also an extreme conditions climate using real data from the literature.

2. Human heat exchange in a hot and dry environment

Air temperature is considered the leading factor in the heat exchange between the human body and the environment. The curiosity about how long the human can withstand high temperatures without detriment to health and what is the upper borderline compelled some individuals to make risky experiments.

2.1. How to stay alive in extreme thermal conditions (Dr Ch. Blagden's historical studies)

On 16 February 1774, at a meeting of the Royal Society in London, Dr Charles Blagden gave a speech on the effects of exposure to extremely high ambient temperatures on the human body. He based his talk on a series of experiments he conducted where he subjected himself and his dog to enormously hot temperatures by staying for 45 min in a room at 126 °C. The dog was resting in the basket to protect his paws from burning in case of direct contact with the ground. In addition, Dr Blagden took a raw steak to the study room. The experiment did not have any adverse health effect on the researcher or his dog, while the steak was cooked to the extent that it could be consumed [11,12]. Human tolerance of such high ambient temperatures has been confirmed in detailed studies by modern physiologists. In one such experiment, producing a similar effect to that performed by Dr Blagden, volunteers were subjected to a temperature of 129 °C for 20 min. In the context of the facts quoted here, the biblical story of the three youngsters thrown at the instructions of King Nebuchadnezzar into the fiery furnace seems to take on a real dimension [13].

What made it possible for the man and his dog to withstand such extreme temperatures without any detriment to their health for so long? The answer lies in the physical properties of the surrounding air. It can be stated with absolute certainty that the air was very dry, and when air is dry, it is a bad conductor of heat, but above all it creates exceptionally good conditions for the process of its reception, especially efficient and used by some living organisms, namely, perspiration.

The maximum content of water vapor in the air depends exponentially on its temperature. At full saturation, i.e., 100% humidity, air temperature of 126 °C contains 1298.5 g/m^3 of water vapor, and its partial pressure reaches 242.25 kPa. It can be assumed with high probability that in the experimental conditions the relative humidity of the ambient air was only about 1%. This corresponds to the steam pressure of 2.4 kPa, i.e., 100 times less than in the state of saturation; in 1 m^3 of air there is 100 times less water vapor, less than 13 g.

These conditions allow shedding of excess heat from the human skin, although intense perspiration is hardly perceptible as the skin appears to be dry. Energy necessary to the perspiration process is provided by surrounding hot and dry air. This is called exogenous heat coming from outside the body. Let us assume that the surface skin temperature t_{sk} of a person staying under these ambient conditions changed over time from about 36 to 40 °C (t_{sk} = 43 °C is considered acceptable in a hot environment) and skin humidity at its surface was 100% due to the sweating process [4]. Then, the water vapor pressure on its surface changed from 5.95 to 7.38 kPa. It was therefore 2.5–3 times higher than the water vapor pressure in the ambient air, which was 2.4 kPa. The difference in pressure between the environment and the skin caused intensive evaporation of sweat from the skin surface. This phenomenon was triggered by a high energy necessary for this process to occur.

The body of an average healthy person can secrete between 1.0 and 1.25 L of sweat within 1 h. The total evaporation of the sweat volume from the skin surface within the hour absorbs power equal to 694–868 W. Over the course of 45 min and in the thermal environment where Dr Blagden's experiment took place, evaporation of about 0.94 kg of sweat absorbed 2420 kJ/kg × 0.94 kg ≈ 2269 kJ (heat of evaporation of sweat is 2420 kJ/kg). If this energy was not used for evaporation of sweat, then the value by which the temperature of a human body with a mass of, e.g., 75 kg could increase by that time would amount to 2269×10^3 J/75 kg / 3490 J/(kg °C) = 8.7 °C. The value of 3490 J/kg °C expresses the value of the specific heat of the body of the mammal. As already mentioned, an increase of body temperature by 1.0–1.5 °C and keeping the internal temperature at 38 °C is considered safe for health [1–4]. If it was not for evaporative cooling, thermal energy from the external environment deposited in the human body would cause Dr Blagden's death after about 31 min, assuming a linear increase in body temperature. The body temperature would then reach approximately 43 °C. There remains, however, the issue of the dog, which, as it is known, does not sweat, but survived the experiment in health thanks to the process of panting, i.e., heat loss in a hot environment due to evaporation occurring from the respiratory tract and a tongue wet with saliva.

This described case of the extreme impact of hot and dry environment on living organisms corresponds to special values of ambient temperature, which by far exceed the body temperature of living beings and extreme conditions of the natural environment in which they exist.

A human can be subjected to less spectacular cases of extreme high temperatures in real life, namely in ambient conditions of desert areas, which currently account for 12% of the land area. But given global warming, such high temperature areas may grow and, in the not too distant future, also encompass some larger cities.

2.2. Computational simulation for a human in a resting state in desert conditions (hot and dry)

To illustrate how a human can adapt to the conditions of the desert climate (hot and dry), calculations were made in accordance with Standard No. EN ISO 7933:2005 [4].

The following environmental conditions were assumed: air temperature $t_a = 50\,°C$, radiation temperature in shade $t_r = 50\,°C$, partial pressure of water vapor $p = 1.23$ kPa, relative humidity $RH = 10\%$, air velocity $V = 0.2$ m/s. The metabolic rate was assumed at $M = 80\,W/m^2$, which corresponds to low physical activity in the sitting position (resting state). Thermal insulation of clothing was assumed at $I_{cl} = 0.6$ clo (underwear, short-sleeved shirt, light trousers, socks, shoes, headgear). The calculations were made for the time interval of 0–480 min.

The results of the calculations made according to Standard No. EN ISO 7933:2005 [4] and presented in Figure 1 show that skin surface temperature t_{sk} and core temperature t_{re} stabilized over time, after about 50 min of exposure to desert environment conditions. This shows that a human body reached equilibrium with the environment, as evidenced by the steady values of $t_{sk} = 35.1\,°C$ and $t_{re} = 37.24\,°C$ that persisted over time. For the condition of equilibrium to be maintained, it is necessary that a human continues to have unrestricted access to drinks that supplement sweat loss, stays in the shade, is exposed to unchanged ambient conditions and refrains from physical activity [14–16].

Figure 2 shows the analysis of heat exchange between the human body and the environment based on the thermal balance equation [1]. The metabolic rate transformations occurring in the body are a source of endogenous heat expressed by the power flux with a density of $M = 80\,W/m^2$, corresponding to a resting state. The skin surface temperature and the core temperature remain lower than the ambient temperature, so the heat is delivered to the body from the environment.

Most heat is delivered to the body via radiation (R). The radiation stream/flux has a power density of $-48.5\,W/m^2$. The minus sign means the flow of heat from the environment to the human body. Slightly less heat is gained by the phenomenon of convection, $C = -39.4\,W/m^2$, i.e., the inflow of heat coming from the air at a temperature of $t_a = 50\,°C$ surrounding a relatively cooler human body. As a result of breathing in air with a temperature higher than the air temperature in the lungs, the body receives heat with a power density of $C_{res} = -1.8\,W/m^2$. Together with the endogenous heat of $M = 80\,W/m^2$, the body is supplied with power from the outside of (M) 80 W/m² + (R) 46.5 W/m² + (C) 39.4 W/m² + (C_{res}) 1.8 W/m² = 167.7 W/m² of the skin surface. Thus, the body can achieve the state of thermal equilibrium with the environment if the heat flow with a power density of 167.7 W/m² is dispersed into the environment due to evaporation of sweat and evaporation of water from the respiratory tract. Low humidity in the surrounding dry desert environment (partial pressure of water vapor 1.23 kPa; $RH = 10\%$) creates favorable conditions for evaporation of water. The calculation of the heat balance shows that the density of the power flow needed for the available amount of sweat to evaporate equals $E = 160.4\,W/m^2$, and the heat loss due to evaporation of water from the airways is $E_{res} = 7.3\,W/m^2$, which balances out the amount of heat entering the body.

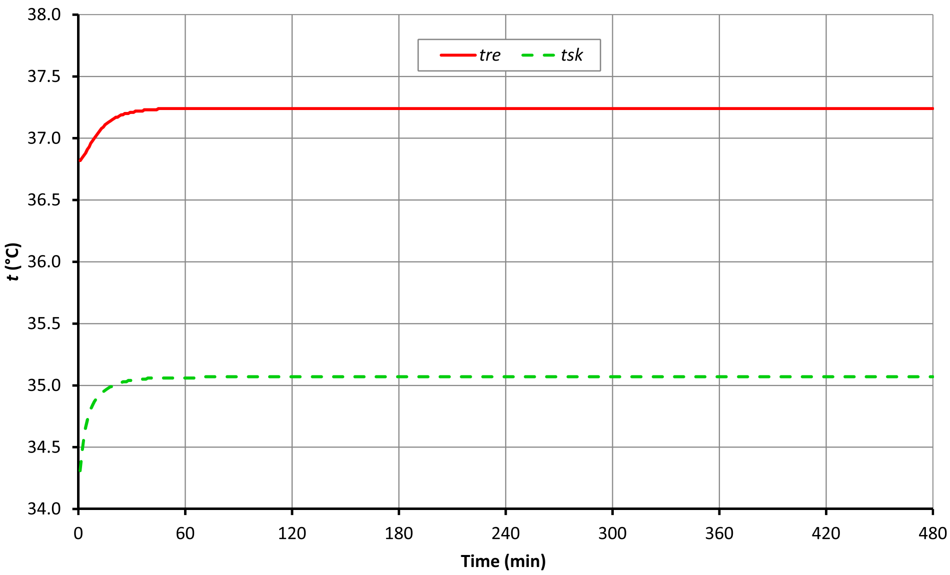

Figure 1. Core temperature (t_{re}, °C) and skin surface temperature (t_{sk}, °C) variability over time for a human body in a hot environment at a temperature $t_a = t_r = 50\,°C$, $RH = 10\%$, $V = 0.2$ m/s, at resting state $M = 80\,W/m^2$, in clothing with thermal insulation $I_{cl} = 0.6$ clo, having unrestricted access to drinks.
Note: Authors' own simulation by the predicted heat strain program. M = metabolic rate; RH = relative humidity; t_a = air temperature; t_r = radiation temperature; t_{re} = rectum core temperature; V = air velocity.

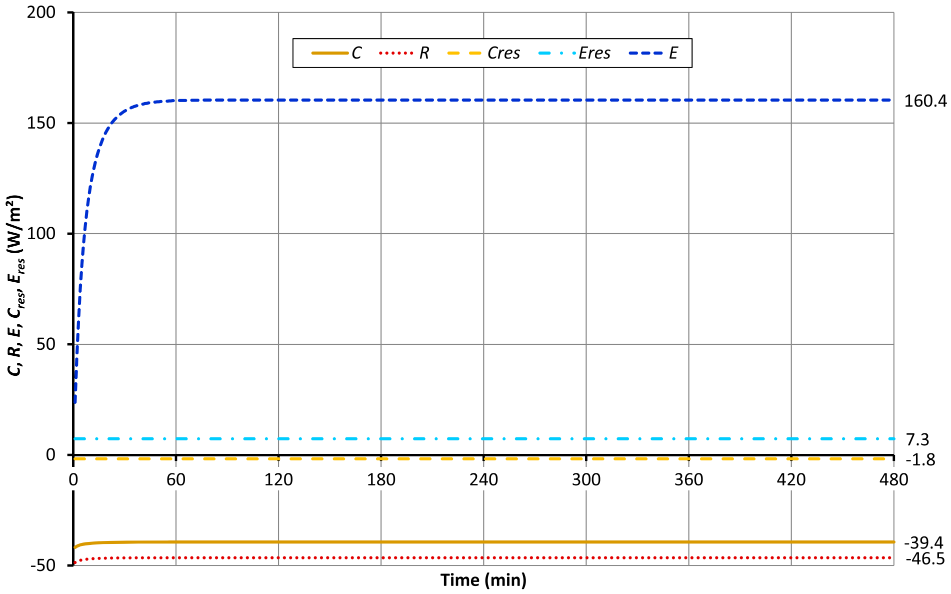

Figure 2. Variability of the thermal balance components over time of C (convection), R (radiation), C_{res} (convection through respiration), E_{res} (evaporation by respiration) and E (evaporation) of a human body in a hot environment with temperature $t_a = t_r = 50\,°C$, $RH = 10\%$, $V = 0.2\,m/s$, at rest $M = 80\,W/m^2$, in clothing with thermal insulation $I_{cl} = 0.6\,clo$, having unrestricted access to drinks.
Note: Numerical values for: C, R, C_{res}, E_{res} and E (W/m²) are shown on the right edge of the figure (authors' own simulation by the predicted heat strain program). M = metabolic rate; RH = relative humidity; t_a = air temperature; t_r = radiation temperature; V = air velocity.

2.3. *Computational simulations for a physically active human in desert conditions (hot and dry)*

In order to check the preservation of the adaptation capabilities of a human performing physical activity in desert conditions, the metabolic rate was increased and assumed to be $M = 130\,W/m^2$, which corresponds to marching without load on a flat terrain at a speed of 2.5 km/h. The environmental conditions and clothing are the same as in the previous example. An artificial assumption has been made that the air temperature is equal to the radiation

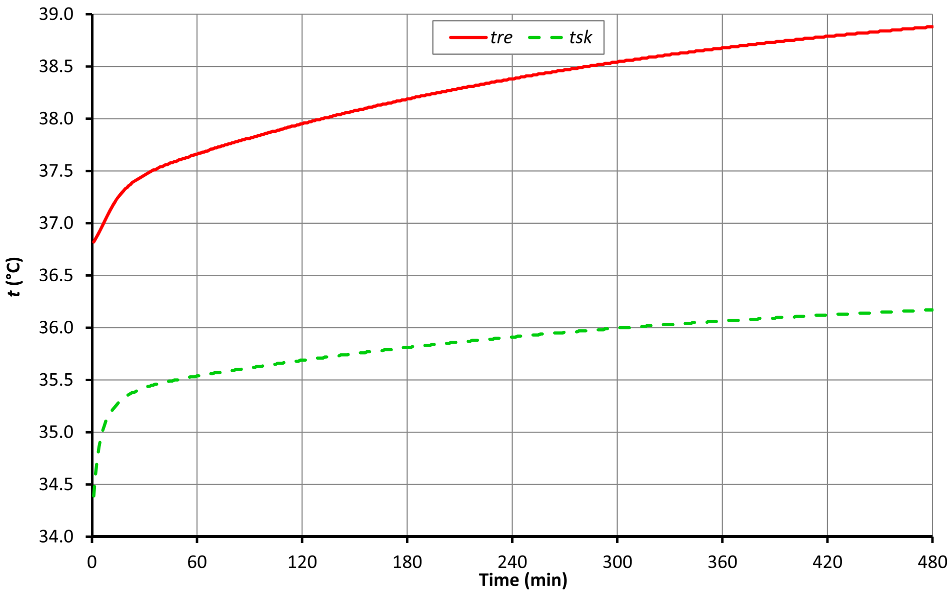

Figure 3. Variability/variations over time in rectum core temperature (t_{re}, °C) and skin surface temperature (t_{sk}, °C) of a human body in a hot environment with temperature $t_a = t_r = 50\,°C$, $RH = 10\%$, $V = 0.2\,m/s$, with the metabolic rate at $M = 130\,W/m^2$, in clothing with thermal insulation $I_{cl} = 0.6\,clo$, having unlimited access to drinks.
Note: Authors' own simulation by the predicted heat strain program. M = metabolic rate; RH = relative humidity; t_a = air temperature; t_r = radiation temperature; V = air velocity.

temperature. The calculations were made for the time interval of 0–480 min.

The results of the calculations are shown in Figure 3. There is an increase over time in the skin surface temperature t_{sk} and core temperature t_{re}, due to the thermal imbalance of the human body with the environment.

After exposure to the desert environment for 130 min, the core temperature reached the threshold value of $t_{re} = 38\,°C$, despite unlimited access to drinks that supplement the loss of sweat. In this case, the heat loss due to the evaporation of sweat is not sufficient to maintain the heat balance with the environment. Given an increased metabolic rate resulting from a greater physical activity and increased secretion of endogenous heat, the body heat accumulation is faster than the rate of its dispersion into the environment. In this case, thermal balance can be restored after physical exertion has been reduced, i.e., lowering the metabolic rate and having a rest in the shade or moving to a cooler environment [14–16]. In natural desert conditions, usually $t_r > t_a$. Therefore, the increase in t_{sk} and t_{re} in time would be higher in real conditions than shown in Figure 3, and the time of reaching $t_{re} = 38\,°C$ would be shorter.

3. Heat transfer in a hot and humid environment

The process of heat emission to the environment caused by evaporative cooling is stopped when the water vapor pressure on the skin surface becomes equal to the water vapor pressure in the environment. If the conditions in the room were those from the 1774 experiment (air temperature set at 126 °C) and the partial water vapor pressure was 5.59 kPa ($RH = 2.5\%$) or 7.38 kPa ($RH = 3\%$), the sweat evaporation process from Dr Blagden's skin surface would have been effectively blocked. The experiment would have lasted only several dozen seconds or a few minutes, with the possible effect of scalding the surface of the exposed skin of the researcher.

3.1. *The case of the silver and gold mines in Naica*

In April 2000, miners working in the former silver and gold mine at Naica in Mexico accidentally discovered the Crystal Cave [17]. It lies almost 300 m below the surface of the Earth and contains unique selenite crystals. The largest crystals are over 11 m long and weigh approximately 55 tons. The environmental conditions where crystals are present, in a form that does not change over time, are lethal for people. The temperature reaches 65.5 °C and air humidity is 100%. The entrance to the cave has been secured with steel gates. This precaution has been put in place to keep environmental conditions unchanged, and to protect the crystals against their destruction but also for fear of attempts to steal them. Despite this protection, one of the miners entering such an 'aggressive' environment probably did not realize the consequences of his deed. His body, much colder than the environment, became the object on which the vapor contained in the air began to condense rapidly. At 65.5 °C and relative humidity $RH = 100\%$, the water vapor pressure is 25.6 kPa, whereas inside the human lungs, at a temperature of about 38 °C and 100% saturated with water vapor, it reaches 6.6 kPa. Thus, the pressure of water vapor in the environment exceeded 3.9 times the vapor pressure in the air filling the lungs. The intensive condensation of water vapor in the lungs was probably the main cause of the rapid death of the miner. One could say that the miner drowned in his own breath.

This described situation clearly shows that a hot and humid environment creates more serious problems for living organisms compared to the dry environment and the lack of access to drinking water. This is due to the fact that in a hot environment, high humidity impairs the transfer of heat from the human body. Such thermal conditions pose a particular hazard to workers in the hot working environment of deep mines [18–21].

3.2. *Computational simulations for a human in a resting state in conditions with low air flow (hot and humid)*

Thermal values $t_a = t_r = 50\,°C$ were used to calculate the heat balance, the same as in the example discussed in Section 2.2. However, the relative humidity was increased from $RH = 10\%$ to $RH = 70\%$ (water vapor pressure $p_a = 8.6$ kPa). The values of the other parameters did not change, i.e., $V = 0.2$ m/s, $M = 80\,W/m^2$ and thermal insulation of clothing $I_{cl} = 0.6$ clo.

An increase of the relative air humidity from 10 to 70% upsets thermal equilibrium between the body and the environment. Such imbalance of thermal conditions effectively blocks sweat evaporation. As shown in Figure 4, the body temperature reached $t_{re} = 38\,°C$, hence the safe exposure time for human health is 23 min. In such thermal conditions, fluid supplementation is irrelevant for the heat balance between the human body and the environment because sweat exuded in profuse quantities will not evaporate and the water loss from the body will be small at this time.

Metabolic changes in the body are a source of endogenous heat, expressed by the power flux with a density of $M = 80\,W/m^2$. The surface skin temperature and the core temperature remain lower than the ambient temperature and increase over time, because exogenous heat is delivered to the body. At the 35th minute of exposure to the environment under consideration, a human body is affected by heat flux with a density of $R = -40.3\,W/m^2$, $C = -33.0\,W/m^2$, $C_{res} = -1.2\,W/m^2$ and $E_{res} = -1.5\,W/m^2$ (Figure 5). Together with endogenous heat of $80\,W/m^2$, a thermal power flux density is supplied to the body:

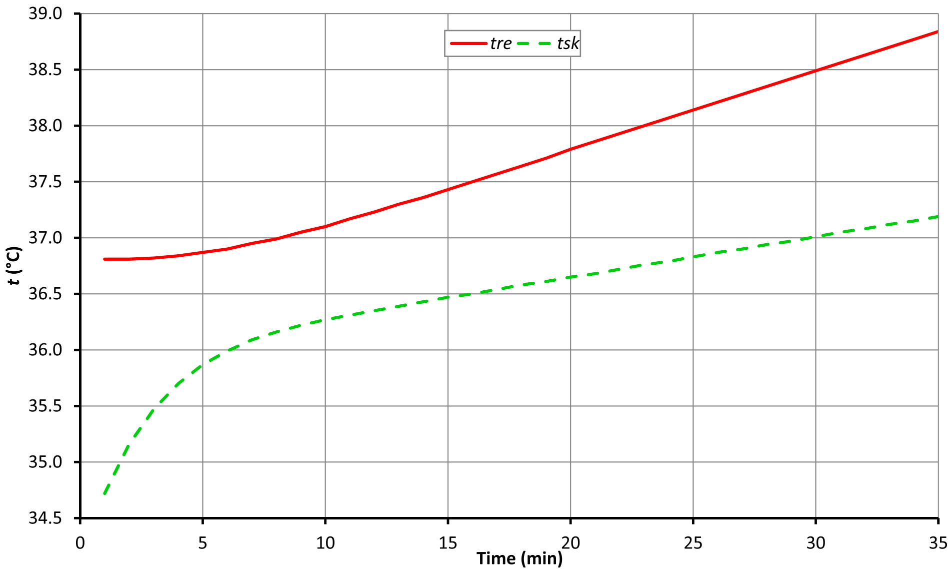

Figure 4. Variability over time of core temperature (t_{re}, °C) and skin surface temperature (t_{sk}, °C) of a human in a hot environment at a temperature $t_a = t_r = 50$ °C, $RH = 70\%$, $V = 0.2$ m/s, at rest $M = 80$ W/m^2, in clothing with thermal insulation $I_{cl} = 0.6$ clo, having unrestricted access to drinks.
Note: Authors' own simulation by the predicted heat strain program. M = metabolic rate; RH = relative humidity; t_a = air temperature; t_r = radiation temperature; V = air velocity.

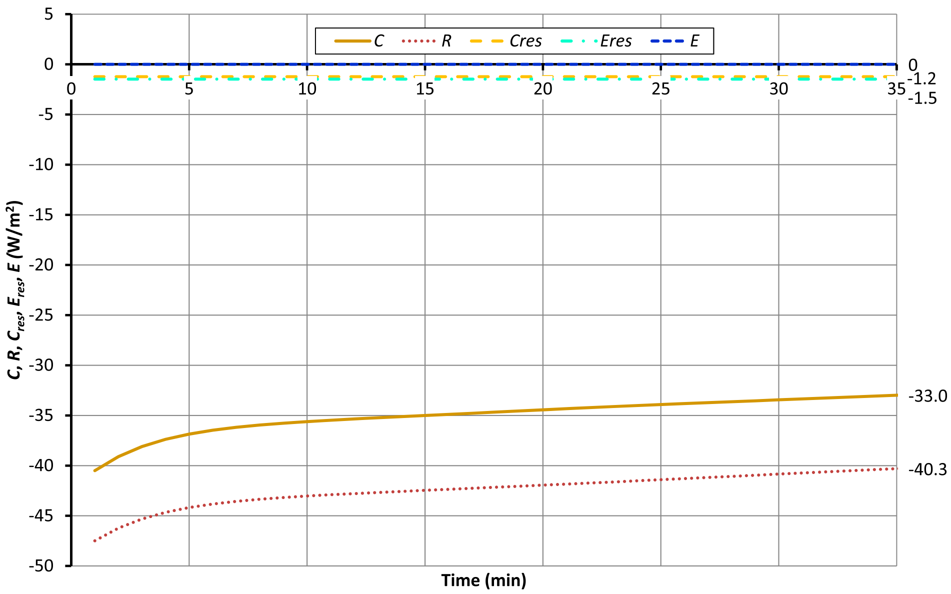

Figure 5. Variability over time of the thermal balance components of C (convection), R (radiation), C_{res} (convection through respiration), E_{res} (evaporation by respiration) and E (evaporation) for a human in a hot environment with temperature $t_a = t_r = 50$ °C, $RH = 70\%$, $V = 0.2$ m/s at rest $M = 80$ W/m^2, in clothing with thermal insulation $I_{cl} = 0.6$ clo, having unrestricted access to drinks.
Note: On the right edge of the figure there are numerical values for C, R, C_{res}, E_{res} and E (W/m²) (authors' own simulation by the predicted heat strain program. M = metabolic rate; RH = relative humidity; t_a = air temperature; t_r = radiation temperature; V = air velocity.

(M) 80 W/m² + (R) 40.3 W/m² + (C) 33.0 W/m² + (C_{res}) 1.2 W/m² + (E_{res}) 1.5 W/m² = 156 W/m². A human body would be able to achieve the state of thermal equilibrium with the environment by the 35th minute of exposure if the heat flux supplied to the body with a power density of 156 W/m² could be dispersed into the environment by evaporation of sweat and evaporation of water from the respiratory tract. Meanwhile, heat losses associated with evaporation are $E = 0$ W/m², while E_{res} is -1.5 W/m². High humidity in the surrounding environment $RH = 70\%$ prevents evaporation of sweat and moisture from the respiratory tract.

3.3. Computational simulations conducted for a physically active human in conditions with low air flow (hot and humid) – Amazon Rainforest

Conditions specific for the forested regions of the Amazon Rainforest were adopted to make computational simulation of the thermal balance, i.e., $t_a = 37\,°C$, $p_a = 4.43$ kPa, $RH = 70.6\%$, $V = 0.2$ m/s, $M = 150$ W/m^2, $W = 30$ W/m^2 and thermal insulation of clothing $I_{cl} = 0.4$ clo [22].

The analysis presented in Figure 6 shows a lack of thermal balance between the human body and the environment. Given that the core temperature of $t_{re} = 38\,°C$ was reached, the exposure time should be limited to 73 min.

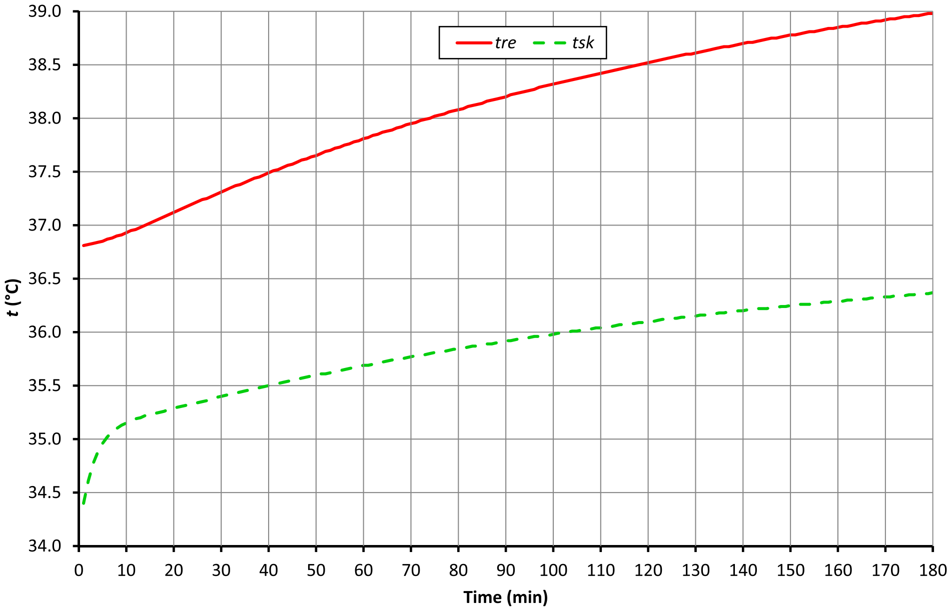

Figure 6. Variability over time in rectum core temperature (t_{re}, °C) and skin surface temperature (t_{sk}, °C) of a human in a hot and humid environment (Amazon Rainforest) with a temperature $t_a = t_r = 37\,°C$, $RH = 70.6\%$, $V = 0.2$ m/s, with the metabolic rate $M = 150$ W/m^2, load 30 W/m^2, in clothing with thermal insulation $I_{cl} = 0.4$ clo, with unlimited access to drinks.
Note: Authors' own simulation by the predicted heat strain program. M = metabolic rate; RH = relative humidity; t_a = air temperature; t_r = radiation temperature; V = air velocity.

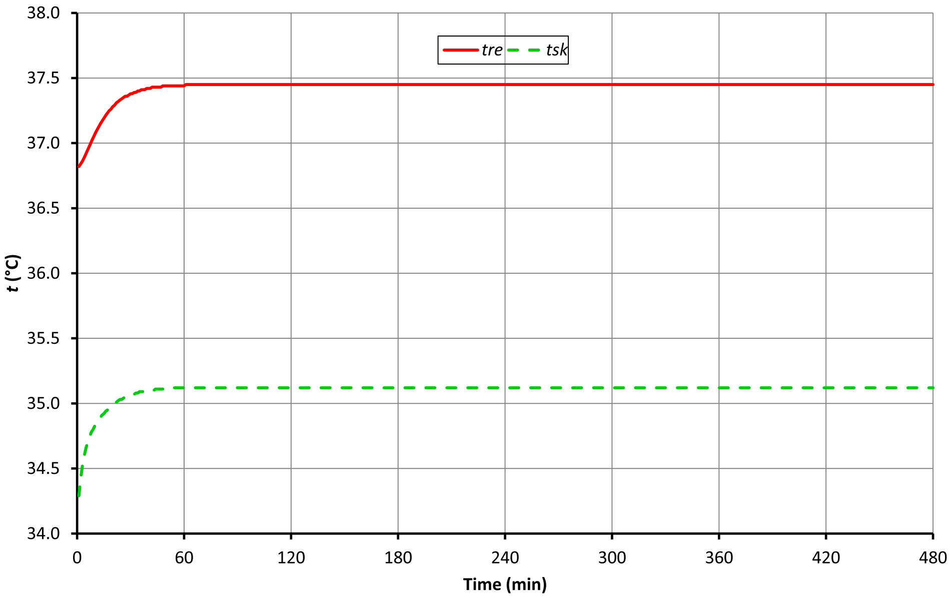

Figure 7. Course of variation/variability over time of the rectum core temperature (t_{re}, °C) and skin surface temperature (t_{sk}, °C) of a human in a hot and humid environment (Amazon Rainforest) with a temperature $t_a = t_r = 37\,°C$, $RH = 70.6\%$, $V = 1.5$ m/s, with the metabolic rate $M = 150$ W/m^2, load 30 W/m^2, in clothing with thermal insulation $I_{cl} = 0.4$ clo, with unlimited access to drinks.
Note: Authors' own simulation by the predicted heat strain program. M = metabolic rate; RH = relative humidity; t_a = air temperature; t_r = radiation temperature; V = air velocity.

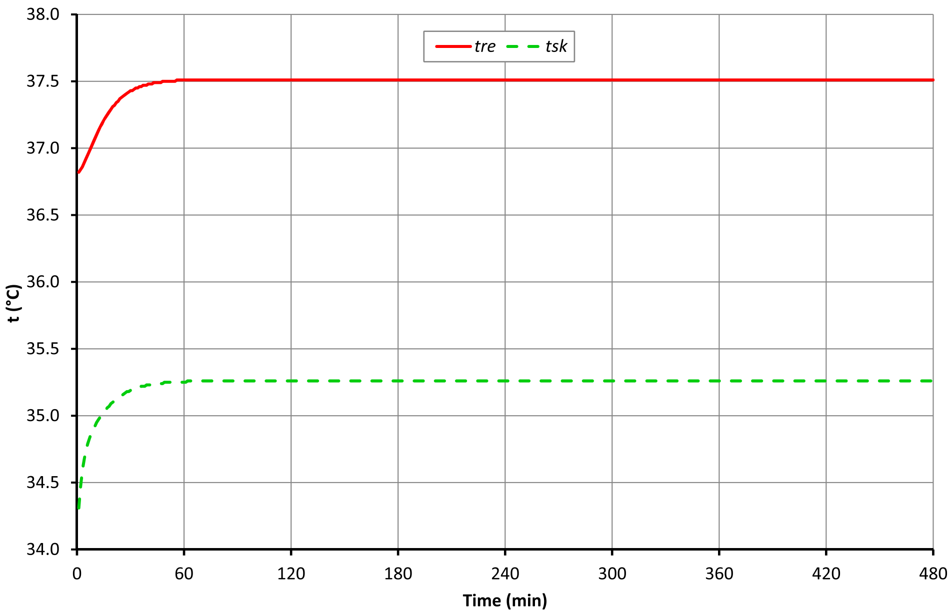

Figure 8. Variability over time in rectum core temperature (t_{re}, °C) and skin surface temperature (t_{sk}, °C) for a human in a hot and humid environment (Ghana) with temperature $t_a = 31.8$ °C, $t_r = 49.8$ °C, $RH = 69.4\%$, $V = 1.9$ m/s, with the metabolic rate $M = 150$ W/m^2, power load 30 W/m^2, in clothing with thermal insulation $I_{cl} = 0.4$ clo, having unrestricted access to drinks.
Note: Authors' own simulation by the predicted heat strain program. M = metabolic rate; RH = relative humidity; t_a = air temperature; t_r = radiation temperature; V = air velocity.

Under these conditions, employees should be given unlimited access to drinks.

3.4. *Computational simulations conducted for a physically active human in conditions with noticeable air flow (hot and humid) – Amazon Rainforest*

For more intensive air flow in the condition characteristic of the Amazon Rainforest climate, the following environmental conditions were adopted: $t_a = 37$ °C, $p_a = 4.43$ kPa, $RH = 70.6\%$, $V = 1.5$ m/s, $M = 150$ W/m^2, $W = 30$ W/m^2 and thermal insulation of clothing $I_{cl} = 0.4$ clo [22].

The analysis presented in Figure 7 shows the thermal balance between the human body and the environment. An increase in the air velocity from $V = 0.2$ m/s to $V = 1.5$ m/s effectively improved working conditions. The exposure time under these conditions can last up to 480 min. However, employees must be given unlimited access to drinks.

3.5. *Computational simulations for a physically active human in conditions with higher air flow (hot and humid) – Ghana*

Environmental conditions specific for Ghana and described by McNeill [23] were adopted to make computational simulations. These were as follows: $t_a = 31.8$ °C, $t_r = 49.8$ °C, $p_a = 3.26$ kPa, $RH = 69.4\%$, $V = 1.9$ m/s, $M = 150$ W/m^2, $W = 30$ W/m^2 and thermal insulation of clothing $I_{cl} = 0.4$ clo (Figure 8).

The analysis of variability over time of the core temperature and the surface skin temperature t_{sk} (Figure 8) shows the thermal equilibrium between the human body and the environment. The exposure time under these conditions can be considered unlimited, i.e., 8 h, since the threshold value of $t_{re} = 38$ °C is not reached. However, employees must have access to drinks.

4. Summary

This article places special emphasis on the significance of the impact of air humidity expressed by water vapor pressure (not only by relative humidity) in relation to the value prevailing inside the human lungs. The computational simulations presented in the article were developed on the basis of the PHS program according to Standard No. EN ISO 7933:2005 [4]. They illustrate the human body response to the extreme conditions of hot and dry or hot and humid environments.

Table 2 summarizes the input data and results of simulation calculations carried out using the PHS program.

4.1. *Hot and dry environment*

In desert conditions at an ambient temperature of 50 °C, with low air movement ($V = 0.2$ m/s), the skin surface temperature t_{sk} and the core temperature t_{re} of a human in the resting state ($M = 80$ W/m^2) (Table 2, no. 1) stabilized over time at a health-safe level already after about 50 min of exposure to a desert environment. This indicates that the human body reached thermal balance with the environment. To maintain such a condition of equilibrium, a

Table 2. Summary of simulation calculations according to the predicted heat strain program.

No.	Section in this article	Input data t_a (°C)	t_r (°C)	p_a (kPa)	RH (%)	V (m/s)	M (W/m^2)	W (W/m^2)	I_{cl} (clo)	Output data Time to reach t_{re} = 38 °C (min)
1	2.2	50.0	50.0	1.23	10.0	0.2	80	–	0.6	480 (t_{re} = 38 °C not reached)
2	2.3	50.0	50.0	1.23	10.0	0.2	130	–	0.6	130
3	3.2	50.0	50.0	8.63	70.0	0.2	80	–	0.6	23
4	3.3	37.0	37.0	4.43	70.6	0.2	150	30	0.4	73
5	3.4	37.0	37.0	4.43	70.6	1.5	150	30	0.4	480 (t_{re} = 38 °C not reached)
6	3.5	31.8	49.8	3.26	69.4	1.9	150	30	0.4	480 (t_{re} = 38 °C not reached)

Note: I_{cl} = thermal insulation of clothing; M = metabolic rate; p_a = partial pressure of water vapor; RH = relative humidity; t_a = air temperature; t_r = radiation temperature; t_{re} = rectum core temperature; V = air velocity; W = work power.

human needs to have access to drinks to supplement sweat loss, stay in the shade, refrain from physical activity and be exposed to unchanged conditions of the surrounding microclimate.

In conditions of a desert climate, but during physical activity corresponding to marching without any load (M = 130 W/m^2) (Table 2, no. 2) that causes an increase of endogenous heat, the body heat accumulation grows at a rate faster than can be dispersed into the environment. After 130 min of exposure to the desert environment, the core temperature reached the threshold value of t_{re} = 38 °C, despite unlimited access to drinks that supplement the loss of sweat. In this case, the heat loss due to the evaporation of sweat is not sufficient to maintain the heat balance of the body with the environment and a return to thermal equilibrium is possible either after reduction of the physical effort, i.e., a reduction of the metabolic rate and rest in the shade or after changing the environment to a cooler one.

4.2. Hot and humid environment

In an ambient air temperature of 50 °C, low air flow velocity (V = 0.2 m/s) and relative humidity of 70%, the safe exposure time for a resting human (M = 80 W/m^2) (Table 2, no. 3) is only 23 min. Such a short time limit is caused by lack of evaporation of sweat, as evaporative cooling is blocked under these conditions. In the case of hot climate conditions (37 °C) with RH = 70.6% and low air flow velocity (V = 0.2 m/s) (Table 2, no. 4), the exposure time for a human with metabolic rate M = 150 W/m^2, loaded with W = 30 W/m^2, is 73 min. This is the time limit before the body temperature safety limit (38 °C) is reached. High humidity in the surrounding environment (RH = 70%) blocks evaporation of sweat and water from the respiratory tract.

At an unchanging ambient temperature of 37 °C, an increase of the airflow velocity from 0.2 m/s (Table 2, no. 4) to 1.5 m/s (Table 2, no. 5) effectively improved the working conditions. The exposure time under these conditions can last up to 480 min. However, with ambient air temperature at 31.8 °C, 69.4% humidity and air velocity at 1.9 m/s (Table 2, no. 6), a physically active human (150 W/m^2) will need about 50 min to reach thermal equilibrium with the environment. The stabilization of the core temperature indicates that the exposure time under these conditions (480 min) can be considered unlimited provided there is constant access to drinks and microclimate parameters remain unchanged.

5. Conclusions

A hot and dry environment, demanding and difficult as it is, creates the possibility of moderate physical activity (with unrestricted access to drinking water) with no health hazards. The results of the calculations show that a hot and dry environment (50 °C air temperature and 10% relative humidity) allows physical activity (with metabolic rate 130 W/m^2) for over 120 min.

Despite access to drinking water, a hot and humid environment causes more serious problems to living organisms than a dry environment. The results of the calculations show that a hot and humid environment (50 °C air temperature and 70% relative humidity) allows low physical activity for only 23 min.

The high partial pressure of water vapor contained in the air has a decisive influence on the heat exchange conditions in a hot environment. It limits or prevents lowering of the body temperature by the most effective heat exchange process in these conditions, namely, evaporation of sweat from the skin. In these circumstances, any chance of physical activity is only possible in conditions of intense air flow.

The results of the described observations, tests and simulations can be important in the development of a system to improve working conditions in deep mines, which are characterized by high temperature and humidity.

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