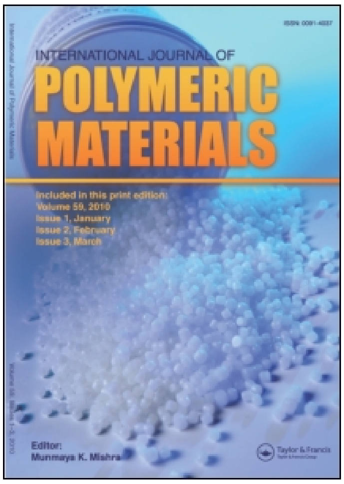

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Rapidity of Human Bodyundercooling or Overheating in Unfavorable Conditions

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A human being must frequently act in an inconvenient environment (too high or too low temperature, contaminated–toxicated atmosphere, *etc.*), without having any possibility of changing the amount of clothing. Besides, the adjustment to the environmental conditions by varying the amount of heat emitted through the skin surface into the environment is limited. In such cases it is of primary importance to determine the period of time available to a subject to act in such unfavorable conditions.

We have developed the method for sufficient precise determination of the time in which a subject may stay or work, without being seriously damaged, in extreme conditions that might lead to overheating or undercooling of his or her body.

Keywords: Thermal resistance; clothing; tolerance interval; wind velocity; environment; heat emission; humidity

INTRODUCTION

In everyday life we are frequently forced to act in extremely dangerous situations such as fire extinguishing and people rescuing from burning buildings, work in the open air at low temperatures, work in open or closed contaminated areas, *etc.* In such situations it is usually impossible to àdjust the amount of clothing to circumstances – there is not additional layers of clothing available in case of the body cooling down, no possibility of changing clothing in contaminated areas due to the risk of respiratory tract or skin toxication (poisonous gases, *etc.*). It is therefore very important to be able to predict the period of time (the tolerance interval) available to a subject to stay or work in such dangerous conditions without suffering any serious damage.

It is very difficult to precisely determine the tolerance interval due to the influence of many various parameters, such as air temperature and humidity, wind velocity and direction, quantity and quality of clothing, its style and shape, its state (wet or dry), quality of its outer layer surface, properties of its outer layer (air and vapour permeable, waterproof, *etc.*), type and intensity of performed work, the observed subject's mental and physical state, *etc.*

The measurements can be carried out on subjects. This is not possible in contaminated areas due to potential of toxication, but it is possible to test all other situations. Since such situations occur very frequently (each change of clothing requires a new test), it is easier and more cost effective to calculate the tolerance interval for the most usual situations and to test on subjects only few most typical states.

We have developed the method for determining the tolerance interval for each state of the environment, clothing and subject's organism. Certain presumptions that are not always in accordance with actual situations (*e.g.*, wind direction, protection of extremities, thermoinsulating value of body superficies, influence of clothing outer layer quality to rapidity of sweat emission, *etc.*) have been taken into consideration. Despite these deficiencies the method can be used in actual situations, particularly if accompanied by additional tests on subjects for some most frequent states in extreme circumstances.

THEORY

The initial state is the state of comfort. The subject is in the state of comfort in the environment in which he will perform certain activity. This applies particularly to closed contaminated buildings. In case of outdoor acting, the subject will be initially in the zone of comfort. After a while the situation may change and the subject begins to warm up or to cool down. The basic presumption in this experiment is the unchangeable composition of clothing. The subject has no additional parts of clothing to put on in case of cooling down and no possibility of taking off any layer of clothing in case of warming up. We also presume that the subject performs the activity with constant intensity and therefore emits constant amount of heat through skin into the environment as well as that his extremities are protected equally as other parts of his body. All calculations are made for a flat surface through which less heat is emitted than through a cylindrical or spherical one. Generally, the thermal resistance of clothing is expressed by the well known Eq. (1):

$$R_c = \sum_i \frac{d_i}{\lambda_i} = \frac{d_c}{\lambda_c} \tag{1}$$

A stable air layer at the surface of clothing also provides certain thermal resistance that may be expressed by the experimentally determined equation [1]. However, the thermal resistance of this layer depends upon wind velocity and this dependence is expressed by Eq. (2):

$$R_a = \frac{0,0429}{0,4 + 2,0\sqrt{v}} \tag{2}$$

Total thermal resistance can be expressed by the following equation:

$$R_c = R_s + R_a \tag{3}$$

Thermal resistance of clothing varies with wind velocity, humidity of clothing and its temperature. The changes can be expressed by the change of the coefficient of thermal conductivity λ_c. This dependence can be expressed by equation for flat surface [2]:

$$\lambda_c = \lambda_0(1 + k_T T + k_W W) + bc_a \gamma_a V d_c \tag{4}$$

Considering Eqs. (1), (2) and (4) the total thermal resistance of clothing and stable air layer at its surface (Eq. (3)) can be expressed by the following equation:

$$R_s = \frac{ad_c}{\lambda_0(1 + k_T T + k_W W) + bc_a \gamma_a V d_c} + \frac{0,0429}{0,4 + 2,0\sqrt{v}} \tag{5}$$

In the zone of comfort the temperature at thorax surface is about 33°C and 37°C in the body core. The average body temperature T_{av}

is defined by the following equation [3]:

$$T_{av} = a_s T_s + b_k T_k \tag{6}$$

Overheating or undercooling of a subject's organism occurs when heat generation and heat emission are in unequilibrium. When less heat is generated than emitted through skin or clothing into the environment, the subject's average body temperature decreases. In the opposite case heat is accumulated in the organism and the body temperature increases. If we known the average body temperature in the initial (the zone of comfort) and final state, the mass of the subject and the specific heat of the body c_b, we can define heat rebalance by the following equation:

$$\Delta Q_b = c_b G(T_{av2} - T_{av1}) \tag{7}$$

$$\Delta Q_b = Q_1 - (Q_2 + Q_3 + Q_4) \tag{8}$$

In Eq. (8) heat Q_1 refers to the fraction of generated heat in the body which does not include heat needed for muscles and internal organs functioning. Q_2 refers to the fraction of heat emitted through skin and clothing directly into the environment. A certain amount of generated heat is used for sweat evaporation (Q_3) and during respiration process (Q_4). In the process of cooling down a relatively small amount of heat is used for sweat evaporation because in this state the organism excretes or evaporates only a negligible amount of sweat. In the process of warming up, however, the losses of heat due to sweat evaporation are extremely important in order to avoid overheating and to prolong the tolerance interval; these losses will be, therefore, considered in the process of overheating.

Heat Q_4 emitted by the subject into the environment during respiration process depends upon the temperature difference between the body core and the environment, relative humidity in the environment, type and intensity of the performed activity, number of inhalations and exhalations in a time unit and amount of inhaled air, respectively. These losses shorten the time needed to reach the critical state in the cooling down process and extend it in the warming up process.

In Eqs. (1) to (8) the symbols mean: R_c – thermal resistance of clothing, $m^2 \cdot h \cdot °C/kJ$; d_c – clothing thickness, m; λ_c – coefficient of clothing heat conductivity, $kJ/m \cdot h \cdot °C$; R_a – thermal resistance of stable air layer at clothing surface; v – wind velocity, m/s; R_s – total thermal resistance of clothing and stable air layer at clothing surface; λ_0 – coefficient of dry clothing heat conductivity at clothing temperature, (0°C) in still weather; k_T – heat conductivity coefficient/clothing temperature dependence curve coefficient ($k_T = 0{,}0025$)[4]; k_W – heat conductivity coefficient/% of humidity in clothing dependence curve coefficient ($k_W = 0{,}04$); W – percentage of water in clothing; $a = b = 1$ – coefficients illustrating tightening properties of clothing (1 = clothing with good tightening properties as is our case); c_a – specific heat of air (0,966 kJ/kg · °C); λ_a – air density ($1{,}2\,\mathrm{kg/m^3}$); V – velocity of air flow through clothing at defined wind velocity, $\mathrm{m^3/m^2 \cdot h}$; T_{av} – average body temperature (in the zone of comfort = 36,6°C); a_s – body superficies share (in the zone of comfort about 0,2); T_s – average body superficies temperature (in the zone of comfort about 35°C); b_k – body core share in the zone of comfort (about 0,8); T_k – body core temperature (in the zone of comfort, 37°C); ΔQ_b – difference between the amount of generated heat that is not used for muscles and internal organs functioning and emitted heat into the environment (in the zone of comfort $\Delta Q_b = 0$), $\mathrm{kJ/m^2 \cdot h \cdot °C}$; c_b – specific body heat, 3,5 kJ/kg · °C; G – body mass, kg; T_{av1} – average body temperature in the zone of comfort (36, 6°C); T_{av2} – average actual body temperature, °C.

The generated heat Q_1 may be measured or taken from literature. In a contaminated environment the subject performs different activities with different intensity and generates different amounts of heat in defined time intervals. Nevertheless, we may use an average value that is most probable with regard to the type and intensity of activity performed by the observed subject. In a contaminated environment we cannot directly measure the amount of emitted heat but similar conditions can be simulated. The sums of heat losses (Q_2, Q_3 and Q_4) can be identical to the amount of generated heat (the zone of comfort), bigger (undercooling) or smaller (overheating).

$$\Delta Q_b = Q_1 - Q_2 = \frac{T_{sk} - T_{en}}{R_{s1}} - \frac{T_{sk} - T_{en}}{R_{s2} + \Delta R_{ti}} = T_{sk} - T_{en}\left(\frac{1}{R_{s1}} - \frac{1}{R_{s2} + \Delta R_{ti}}\right) \tag{9}$$

Heat Q_3 (the loss of heat due to sweat evaporation) is very important in the zone of overheating. Reduction of the body superficies and clothing thermoinsulation and of the wind velocity also has positive effect. The same applies to heat Q_4, however, it may be neglected. In the zone of undercooling only the augmentation of thermoinsulating value of the body superficies has positive effect. Heat Q_3 can be defined by the following equation:

$$Q_3 = c_w\varphi\left[a_1\frac{T_{sk}+T_{en}}{2}+a_2v^n\right]^m \tag{10}$$

$\varphi = (100 - RH)/100$, where RH is relative air himidity expressed in %. The inhaled air is saturated with water vapours and warms up or cools down to the body core temperature T_k, depending on the temperature of inhaled air. The amount of heat Q_4 that is consumed during respiration process can be defined by the following equation:

$$Q_4 = (T_k + T_{en})V_a(c_w\varphi g_w + c_a\gamma_a) \tag{11}$$

In Eqs. (7) to (10) heat is expressed in $\mathrm{kJ/m^2 \cdot h}$. The body surface of an average subject is about 1,8 $\mathrm{m^2}$. Observations usually lasts less or more than an hour. In Eq. (11) heat is expressed in kJ/h. The amount of heat generated or lost by the observed subject in a defined period of time is calculated by multiplying right sides of Eqs. (9) and (10) with the body surface (1,8 $\mathrm{m^2}$) and the time of observation t. The right side of Eq. (11) is also multiplied with the time t and Eq. (8) solved after the time t.

$$t = \frac{\Delta Q}{S}(R_{s2}+\Delta R_{ti})R_{s1} \Bigg/ \Bigg[(T_{sk}-T_{en})[(R_{s2}+\Delta R_{ti})-R_{s1}] - Rs1(R_{s2}+\Delta R_{ti})c_w\varphi \times\left[a_1\left(\left(\frac{T_{sk}+T_{en}}{2}\right)^m + a_2v^n\right) + \left(g_w+\frac{c_a\gamma_a}{c_w\varphi}\right)V_a\frac{T_k-T_{en}}{S}\right]\Bigg] \tag{12}$$

In Eqs. (9) to (12) the symbols mean: T_{sk} – temperature at skin surface, °C; T_{en} – temperature of environment, °C; ΔR_{ti} – change of the body superficies thermal resistance according to the state in the zone of comfort; c_w – specific heat of water evaporation; a_1 and a_2 – coefficients of regression curve; in our experiments $3 > m > 1$; $0,5 < n < 1$;

g_w – amount of water vapours in an air volume unit at the body core temperature; V_a – amount of exhaled air during the observation time, m^3/h; t – time in hours required to achieve critical temperature of the subject's body undercooling or overheating.

DISCUSSION

Equation (12) represents a general solution for defining the period of time (the tolerance interval) during which a subject may, without suffering serious damages, perform certain activity in extreme conditions that might lead to the subject's body undercooling or overheating. ΔQ_b (Eq. (7) is the amount of heat that may be additionally taken from the subject's organism to enable it to cool down to the critical mean value, *e.g.*, 30°C, or to prevent accumulation of more heat than is necessary for increase of the body mean temperature to the critical value, *e.g.*, 39°C. The presumption is that the protective clothing tightens firmly on openings (end of sleeves, both ends of trousers, waist, collar, *etc.*), otherwise clothing is air and vapours permeable. Toxic gases are absorbed by a special active layer (activated graphitized fabric *etc.*) That's why the value of coefficients is $a = b = 1$.

It is difficult to determine the velocity of sweat evaporation. In the first approximation we presumed that sweating and sweat evaporation may be neglected in the zone of comfort and cooling down. In the zone of warming up (accumulation of heat), however, sweating is intensive and the clothing gets soaked with sweat. The surface of clothing becomes wet. The velocity of evaporation was measured in standard atmosphere (21°C and 69% RH). The temperature at wet fabric surface was gradually rising from 20°C (wet thermometer) to 45°C. The rapidity of evaporation was measured at wind velocity 0 to 5 m/s at angle of blowing 45 degrees. We presumed that the temperature of sample is the same as the temperature of the clothing surface that evaporates sweat. This presumption is not quite correct because the temperature in the zone of evaporation decreases due to heat consumption for sweat evaporation. The velocity of sweat evaporation was expressed in $g/m^2 \cdot h$. The angle of wind blowing was 45 degrees. In mentioned conditions of measuring the rapidity of evaporation the value of calculated correlation coefficient is 0,95. Water (sweat) evaporates from a cotton fabric surface faster than from a woolen one. If the outside fabric of clothing is thoroughly wet, it does not permit air through pores in the fabric, so there is no additional surface (inside surface of pores) available for sweat evaporation.

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