UDK 677.017.8 : 536

Izvirni znanstveni članek

red. prof. dr. **Danilo Jakšić**, univ. dipl. inž.
Naravoslovnotehniška fakulteta, Oddelek za tekstilstvo, Snežniška 5, 1000 Ljubljana
e-pošta: danilo.jaksic@guest.arnes.si
dr. **Nikola Jakšić**, univ. dipl. inž.
European Commission, DG-JRC, Institute for Energy, P.O. Box 2, NL - 1755 ZG Petten
The Netherlands; e-pošta: nikola.jaksic@guest.arnes.si

Metoda ugotavljanja časa tolerance v ekstremnih razmerah podhlajanja ali pregrevanja organizma

Če smo izpostavljeni neprijetnemu okolju, ki lahko glede na okoliščine povzroči pregrevanje ali podhlajanje organizma, je življenjsko pomembno ugotoviti čas, ki nam omogoča delovanje v teh razmerah brez nevarnosti poškodbe posameznih delov telesa ali celo smrti. Ta čas lahko imenujemo čas tolerance. Kako hitro se bo organizem podhladil ali pregrel v danih razmerah, je odvisno od številnih dejavnikov, kot so: stanje okolja (temperatura, hitrost vetra, padavine), termoizolacijske lastnosti oblačila, količina izžarjene toplote v okolje v enoti časa, možnost prilagajanja termoizolacijske vrednosti oblačila, psihofizično stanje osebe, ki je izpostavljena ekstremnim razmeram v okolju, ipd.

Pri oblajanju osebe se posamezni deli telesa različno odzivajo na zunanje vplive. Najbolj občutljivi so prsti rok in nog, ušesa, nos in potem stopala in pesti. Posebna obravnava posameznih delov telesa in torza je izjemno težavna in kompleksna. Zaradi poenostavitve obdelave problema podhlajevanja in pregrevanja telesa človeka bomo predpostavili, da je bila opazovana oseba v začetni fazi v coni ugodja v suhem oblačilu, kar pomeni, da je celotno telo primerno toplotno izolirano.

Metoda temelji na primerjavi dejanske toplotne izolacije oblačila in potrebne v obravnavanih stanjih okolja in subjekta. Iz razlik dane in potrebne termoizolacje oblačila se da ugotoviti čas tolerance oziroma čas, ki je potreben, da se telo subjekta ohladi na srednjo kritično temperaturo v razmerah oblajanja. Pri pregrevanju pa dominantno vlogo ima izhlapevanje znoja.

***Ključne besede:** čas tolerance, toplotni upor, oblajanje organizma, pregrevanje organizma, proizvodnja toplote, izžarevanje toplote, oblačilo, subjekt, toplota, vlaga, hitrost vetra, cona ugodja.*

Original Scientific Paper

Prof **Danilo Jakšić**, DSc
University of Ljubljana, Faculty of Natural Sciences and Technology, Department of Textiles, Snežniška 5, SI-1000 Ljubljana; e-mail: danilo.jaksic@guest.arnes.si
Nikola Jakšić, DSc
European Commission, DG-JRC, Institute for Energy, P.O. Box 2, NL - 1755 ZG Petten
The Netherlands; e-mail: nikola.jaksic@guest.arnes.si

Method of Determination of Tolerance Time in Case of Body Cooling Down or Overheating in Extreme Conditions

In unfavourable environmental conditions, overheating or cooling down of a human body may occur. For such cases, it is of vital importance to determine the time available to the concerned person for performing activities without being seriously damaged or fatally impaired. This time can be called the tolerance time. How quickly an organism will cooling down or overheat in given conditions depends on many various factors, such as: environmental conditions (temperature, velocity of wind, precipitation), thermal resistance properties of clothing, amount of heat emitted into the environment in a unit time, possibilities of regulating the thermal resistance value of clothing, mental and physical state of the person exposed to extreme environmental conditions.

In the conditions of cooling down, individual parts of the body react differently to external influences. Most sensitive are fingers, toes, auricles, nose, feet and fists. It would be difficult and time consuming to investigate each part of the body and torso separately. In order to simplify the problem of cooling down and overheating, it is supposed that in the starting phase the observed person is in the zone of comfort and wears dry clothing, which means that the entire body is suitably thermally insulated. The method is based on the comparison of real thermal insulation of clothing and the required one for the investigated conditions of the environment and the state of the observed person. From the differences between real and the required thermal insulation of clothing, it is possible to determine the tolerance time, i.e. the time which is required by a human body to cool down to the mean critical temperature in the conditions of cooling down. In the conditions of overheating, sweat evaporation has a predominant role.

***Key words:** time of tolerance, thermal resistent, cooling down of the body, overheathing of the body, production of the heat, loss of the heat, clothing subject, heat, moisture, velocity of the wind, comfort.*

1.0 UVOD

Človek občasno biva v neprimernem okolju (previsoka ali prenizka temperatura, kontaminirana – zastrupljena atmosfera ipd.), v katerem nima možnosti za spremembo količine oblačila. Poleg tega je omejena tudi prilagoditev s pomočjo spremembe količine izžarene toplote v okolje skozi površino kože. Za takšna izjemna stanja je zelo pomembno ugotoviti čas, v katerem lahko oseba opravlja določene aktivnosti v tem neprimernem okolju. To je področje psihomotorike, v katero se ne bomo podrobneje spuščali. Ko pravimo, da oseba lahko opravlja določene aktivnosti, mislimo na stanje, ko se temperatura na površini prstov rok zniža na manj kot 15 °C. V tem stanju se izredno zmanjša gibljivost prstov rok in zato subjekt ni zmožen opravljati del, za katera je potrebna popolna gibljivost prstov rok.

V realnem življenju smo pogosto prisiljeni delovati v izredno nevarnem okolju. To se nanaša predvsem na gašenje požarov in reševanje ljudi iz gorečih objektov, delo na prostem pri nizkih temperaturah, delo v kontaminirani coni na prostem ali v zaprtih prostorih ipd. V teh stanjih najpogosteje nimamo možnosti za prilagoditev količine oblačila stanju okolja, kar pomeni, da nimamo na voljo dodatnih plasti oblačila, če se začnemo ohlajati. V zastrupljenem okolju ne moremo spreminjati količine oblačila zaradi možnosti zastrupitve dihalnih organov in kože (bojni strupi ipd.). V teh primerih je bistveno realno predvideti čas (lahko ga imenujemo čas tolerance) bivanja in delovanja oseb, v katerem ne bo prišlo do resnejših poškodb telesa.

Izredno težko je natančno ugotoviti čas tolerance. Nanj vpliva veliko parametrov, kot so: temperatura in vlaga okolja, hitrost vetra in njegova smer pihanja, količina in kakovost plasti oblačila, kroj in oblika oblačila, stanje oblačila (suho ali mokro), kakovost površine zgornje plasti oblačila, karakteristike zgornje plasti oblačila (prepustnost za zrak in vodno paro, prepustnost ali neprepustnost za vodo), vrsta in intenziteta dela, ki ga opravlja oseba v izrednih razmerah, psihofizično stanje ipd.

Seveda meritve lahko izpeljemo na ljudeh, vendar ne v zastrupljenem okolju, ker obstoji določena verjetnost zastrupitve. Zato je v tem primeru težko izpeljati verodostojen poskus. Kljub temu je mogoče testirati vsa druga stanja. Teh pa je preveč. Že manjša sprememba v oblačilu zahteva nov preizkus. Zato je preprosteje in tudi ceneje izračunati čas tolerance za vsa stanja, ki bodo najpogosteje nastopila v realnem življenju v izrednih razmerah, in testirati na ljudeh le nekaj najbolj tipičnih stanj.

Razvili smo metodo ugotavljanja časa tolerance v kateremkoli stanju okolja, stanju oblačila in stanju organizma človeka. Pri tem so upoštevane nekatere domneve, ki se zmeraj popolnoma ne ujemajo z realnim stanjem, kot je na primer kot pihanja vetra, zaščita ekstremitet,

1.0 INTRODUCTION

From time to time, a man has to act and stay in an inconvenient environment (too high or too low temperature, contaminated – intoxicated atmosphere, etc.) without having any possibility of changing the amount of clothing. Besides, adaptation by changing the amount of the emitted heat into the environment through the skin surface is limited. For such conditions, it is of vital importance to determine the period of time available to the concerned person for performing certain activities in such unfavourable circumstances. Anyway, this is the matter of the psychomotor science and will not be dealt with in detail in this paper. When we say that a person can perform certain activities, we have in mind the state in which the temperature on the surface of fingers falls below 15 °C. In such state, the motion ability of fingers decreases considerably so that the affected person is not capable of performing works that require total movability of fingers.

In real life, people 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 adjust the amount of clothing to the circumstances, which means that there are no additional layers of clothing available to be put on in the case of body cooling down. In the contaminated environment, it is impossible to change the amount of clothing due to the risk of respiratory tract or skin intoxication (toxic gases, etc.). It is therefore very important to be able to predict the time (it can be called the tolerance time) available to a concerned person to stay or act in such dangerous conditions without suffering any serious damages of the body.

It is very difficult to precisely determine the tolerance time due to the influence of many various parameters, such as: temperature and humidity of environment, velocity and direction of wind, quantity and quality of clothing, style and shape of clothing, state of clothing (wet or dry), quality and properties of its outer layer (air and vapours permeable, waterproof, etc.), type and intensity of the performed work, mental and physical state of the person exposed to extreme conditions, etc.

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

We have developed the method of determining the tolerance time for any state of environment, clothing and organism. Certain presumptions, which are not always in accordance with real situations (e.g. angle of wind blowing, protection of extremities, thermal resistance thermalinusulation value of the body covering, (skin and subcutaneous tissue, which do not have constant temperature, while the body core has constant temperature 37 °C in the zone of comfort), influence of termoizolacijska vrednost plašča telesa (koža in podkožno tkivo, ki nimata stalne temperature v nasprotju z jedrom telesa, ki ima v coni ugodja stalno temperaturo 37 °C), vpliv kakovosti zunanje plasti oblačila na hitrost izhlapevanja znoja ipd. Pri ohlajanju organizma nastane problem zaščite ekstremitet (ušesa, nos, prsti rok in nog). Ušesa, nos in prste nog lahko primerno zaščitimo, da ne nastanejo poškodbe zaradi podhladitve. Problem so pesti in prsti rok. Ne moremo uporabiti rokavic, ki bi onemogočale uporabo rok za opravljanje določenih del. Če vzamemo kot merilo za izračun časa tolerance delovno sposobnost subjekta pri ohlajanju organizma, potem je čas tolerance čas, v katerem se temperatura prstov zniža pod 15 °C. Pri ohlajanju se toplota črpa iz organizma opazovanega subjekta in se zaradi tega znižuje povprečna temperatura telesa. Kako hitro poteka ohlajanje, je odvisno od spremembe termoizolacijske vrednosti oziroma toplotnega upora plašča telesa. Ta se lahko spreminja približno od 0,0343 do 0,0086 m^2.h.°C/kJ, kar je približno osemkratna vrednost [10]. Z ohlajanjem se delež plašča povečuje na račun deleža jedra. Poleg tega se znižuje tudi temperatura jedra telesa. Naš namen ni spuščati se v to področje. Zato se bomo bolj posvetili oceni stanja organizma opazovanega subjekta s tem, da bomo predvideli linearno odvisnost spremembe toplotnega upora plašča telesa v odvisnosti od srednje temperature telesa. Pri pregrevanju organizma je pomemben upor oblačila pretoku vodne pare.

Kljub tem pomanjkljivostim je mogoče metodo uporabiti v realnih primerih, posebno če se še dodatno izpeljejo preizkusi na ljudeh za nekatera najpogostejša stanja, ki bi lahko nastopila v izjemnih okolščinah.

2.0 TEORETIČNO OZADJE

Obravnavali bomo primere, ko lahko pride do pregrevanja in podhlajevanja organizma. Ne bomo obravnali situacij, ki so posledica požarov. V teh primerih so spremembe temperature hitre in drastične. Časi delovanja v teh razmerah pa so zelo kratki. Začetno stanje naj bo stanje ugodja. Človek naj bo v stanju ugodja v okolju, v katerem bo deloval. To se nanaša predvsem na zaprte kontaminirane objekte. Če pa oseba deluje na prostem, naj bo v začetku delovanja v coni ugodja. Stanje ugodje ali cona ugodja je tisto stanje, v katerem je temperatura na površini prsi okrog 33 °C in temperatura jedra telesa 37 °C ter sta proizvodnja in izguba toplote izenačeni. Čez čas se stanje lahko spremeni in oseba se lahko začne segrevati ali podhlajati. Osnovna predpostavka pri tem poskusu je nespremenljiva sestava oblačila. Oseba nima dodatnih delov oblačila, če se je začela podhlajati (alpinizem ipd,), niti nima možnosti odvreči določeno plast oblačila, če se je začela segrevati (kontaminirano okolje). Poleg tega bomo predpostavili, da oseba ves čas opravlja določeno aktivnost

the clothing outer layer quality on rapidity of sweat emission, etc.), have been taken into consideration. In the conditions of a body cooling down, the problem of the protection of extremities (auricles, nose, fingers and toes) occurs. Auricles, nose and toes can be adequately protected against damages due to cooling down but a real problem are fingers and the palm of the hand. Namely, the use of gloves would disable the affected person from performing the activity. If in the conditions of the body cooling down, the person's working ability is considered as the criterion for calculating the tolerance time, the tolerance time will be the time in which the temperature of fingers falls below 15 °C. In the process of cooling down, the heat is exhausted from the observed person's body and as a result, the body mean temperature decreases. How quick the process of cooling down will be depends on the change of the thermal insulating value or the body covering thermal resistance. It can change approximately from 0.0343 to 0.0086 m^2.h. °C/kJ, which is approximately an eightfold value [10]. During the cooling down process the share of the body covering increases on account of the body core share. Besides, the body core temperature decreases as well. However, the purpose of this paper is not to investigate this issue. We will use an approximate estimation of the state of the observed person's organism by assuming linear dependence of the change of the body covering thermal resistance in dependence of the mean body temperature. In the process of the body overheating, it is the resistance of clothing to the water vapour flow which is important.

Despite these deficiencies, the method can be used in real situations, particularly if accompanied by additional tests on people for some most frequent states that might occur in extreme conditions.

2.0 THEORY

The research encompasses the situations in which overheating and cooling down of an organism may occur. The situations resulting from fire will not be dealt with due to quick and drastic changes of temperature and very short time available for acting. The initial state is the state of comfort. The observed person is in the state of comfort in the environment in which he or she is going to perform a certain activity. This refers particularly to closed contaminated facilities. In the case of outdoor activities, the person will be initially in the zone of comfort. The state of comfort or the zone of comfort is the state in which the temperature on the chest surface is about 33 °C and the body core temperature 37 °C and when the production and the loss of heat are level. After a while, the situation may change and the person may start to warm up or cool down. The basic presumption in this experiment is the unchangeable composition of clothing. The person has no additional pieces of clothing to put on in the case of cooling down (mountaineering, etc.) and no possibility of taking off any layer of clothing in the case of warming up (contaminated environment). It is also presumed that the person performs z določeno intenziteto in zato izžareva v okolje stalno količino toplote skozi površino kože, in da so okončine osebe ustrezno zaščitene tako kot drugi deli telesa. Vsi izračuni se nanašajo na ravno površino, skozi katero se sicer izžareva manj toplote kot skozi valjasto ali sferno površino.[15] Na splošno lahko toplotni upor oblačila izrazimo z naslednjo enačbo:

the activity with constant intensity and emits a constant amount of heat through the skin into the environment as well as that the extremities and other parts of the body are adequately protected. All calculations refer to a flat surface through which less heat is emitted than through a cylindrical or spherical surface.[15] Generally, thermal resistance of clothing can be expressed with the following equation:

$$R_c = \sum_i \frac{d_i}{\lambda_i} = \frac{d_c}{\lambda_c} \quad (1)$$

Plast zraka na površini oblačila, za katero pravimo, da je negibna, daje tudi določen toplotni upor, ki ga lahko izrazimo z znano, eksperimentalno ugotovljeno enačbo[1], ki velja pri hitrosti vetra, ki je ≥ 1 m/s. Na toplotni upor te plasti zelo vpliva hitrost vetra. Ta odvisnost je prikazana z naslednjo enačbo:

The motionless air layer on the surface of clothing also provides certain thermal resistance, which can be expressed with a known, experimentally determined equation[1], which applies to the velocity of wind equal or higher than 1 m/s. The velocity of wind has an important influence on thermal resistance of this layer. This dependence is illustrated with the following equation:

$$R_a = \frac{0,0429}{0,4 + 2,0v^{0,5}} \quad (2)$$

Skupni toplotni upor lahko izrazimo z naslednjo enačbo:

Total thermal resistance can be expressed with the following equation:

$$R_s = R_c + R_a \quad (3)$$

Toplotni upor oblačila se tudi spreminja glede na hitrost vetra, količino vlage v oblačilu in spremembe temperature oblačila. Te spremembe lahko izrazimo s spremembo koeficienta toplotne prevodnosti, λ. To odvisnost lahko izrazimo z naslednjo enačbo za ravno površino[2]:

Thermal resistance of clothing also varies in dependence of the velocity of wind, percentage of humidity in clothing and temperature of clothing. These changes can be expressed with the change of heat conductivity coefficient λ. This dependence can be expressed with the following equation for a flat surface[2]:

$$\lambda_c = \lambda_0 \left(1 + k_T \Delta T_c + k_w \Delta G_c\right) + b c_a \gamma_a V_a d_c \quad (4)$$

Če upoštevamo enačbe od 1 do 4, lahko skupni toplotni upor oblačila in mirne plasti zraka na površini le-tega (enačba 3) izrazimo z naslednjo enačbo:

Considering Equations 1 to 4, total thermal resistance of clothing and motionless air layer on its surface (Equation 3) can be expressed with the following equation:

$$R_s = \frac{d_c}{\lambda_0 \left(1 + k_T \Delta T_c + k_w \Delta G_c\right) + b c_a \gamma_a V_a d_c} + \frac{0,0429}{0,4 + 2,0 v^{0,5}} \quad (5)$$

V enačbi 5 smo upoštevali oziroma opisali tesnitev oblačila s koeficientom, *b*. V coni ugodja je temperatura na površini prsi okrog 33 °C, temperatura jedra telesa 37 °C in povprečna temperatura telesa, T_{av} je 36,6 °C. Pregrevanje ali podhlajanje organizma človeka nastopi takrat, ko pride do neravnotežja med proizvodnjo toplote v telesu in oddajanjem le-te v okolje. Če je proizvodnja toplote v organizmu manjša, kot so njene izgube skozi površino kože oziroma zunanjo površino oblačila v okolje, se bo začela zniževati povprečna temperatura telesa opazovane osebe. V nasprotnem primeru se bo toplota začela »skladiščiti« v telesu in se bo začela

In Equation 5, the tightening properties of clothing are described with coefficient *b*. In the zone of comfort, the temperature on the chest surface is about 33 °C, in the body core it is 37 °C and the mean body temperature T_{av} is 36.6 °C. Overheating or under cooling of the human body occurs when heat generation and heat emission are in imbalance. When less heat is generated than emitted through the skin or the outer surface of clothing into the environment, the mean body temperature starts to decrease. In the opposite case, the heat starts to accumulate in the body and the body temperature increases. If the mean body temperature in the initial (the zone of comfort) and final state as well as the mass dvigati telesna temperatura. Če so nam znani povprečni temperaturi telesa v začetnem (cona ugodja) in končnem stanju, teža osebe in specifična toplota telesa, c_b, lahko debalans toplote izračunamo z naslednjo enačbo:

and specific heat of the body c_b are known, the heat imbalance can be defined with the following equation:

$$\Delta Q_b = c_b G_b \left(T_{av2} - T_{av1} \right) \tag{5}$$

Iz enačbe 6 je razvidno, da je debalans toplote pozitiven tedaj, ko se toplota kopiči v telesu osebe, in negativen, če se toplota črpa iz telesa subjekta, tako da se zmanjšuje srednja temperatura telesa. Ta debalans je posledica izgub toplote, ki so lahko večje ali manjše, kot je proizvodnja toplote, ki se izžareva skozi površino kože in kot se porabi za izhlapevanje znoja in segrevanje ali ohlajanje vdihanega zraka. Če je debalans negativen, se oseba podhlajuje, če je pozitiven, se pregreva. V primeru, da ni debalansa ($\Delta Q = 0$) in je bila pred to meritvijo oseba v coni ugodja, je še zmeraj v nespremenjenem stanju. Debalans lahko izrazimo z naslednjo enačbo:

Equation 6 shows that the heat imbalance is positive in the case of heat accumulation in the body and negative in the case of heat emission from the body to such a degree that the mean body temperature decreases. This imbalance is the result of heat losses, which are higher or lower than the heat generated and emitted through the skin surface and the heat used for sweat evaporation and for warming or cooling the inhaled air. When the imbalance is negative, the person is cooling down, when it is positive, the person is overheating. If there is no heat imbalance ($\Delta Q = 0$) and the person was in the zone of comfort before this measurement, he or she is still in the unchanged condition. The imbalance can be expressed with the following equation:

$$\Delta Q_b = Q_1 - \left(Q_2 + Q_3 + Q_4 \right) \tag{7}$$

Posamezne toplote iz enačbe 7 so definirane z enačbami 8 do 11:

Individual heats in Equation 7 are defined with Equations 8 to 11:

$$Q_1 = \frac{\left(T_{skc} - T_{en} \right) St}{R_{s1}} \tag{8}$$

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

$$Q_3 = c_W \varphi \left[a_0 + \frac{a_1 \left(T_{sk} + T_{en} \right)}{2} + a_2 v \right] St \tag{10}$$

$$Q_4 = \left(T_k - T_{en} \right) V_a \left(c_w \varphi G_{aw} + c_a \gamma_a \right) t \tag{11}$$

Enačba 8 velja za cono ugodja tedaj, ko zanemarimo izgube toplote med dihanjem in izgube zaradi izhlapevanja znoja. Če vstavimo v enačbo 7 izraze za posamezne toplote, enačbe od 8 do 11 in enačbo 7 rešimo po času t, dobimo splošno rešitev za izračun časa tolerance – enačba 12.

Equation 8 applies to the zone of comfort when heat losses during respiration and perspiration are neglected. If individual heats in Equation 7 are replaced with expressions in Equations 8 to 11 and Equation 7 solved by time t, a general calculation of the tolerance time is obtained – Equation 12.

$$t = \frac{\Delta Q_b}{\left[\frac{\left(T_{skc} - T_{en} \right) S}{R_{s1}} - \frac{\left(T_{sk} - T_{en} \right) S}{R_{s2} + \Delta R_{ti}} \right] - c_w \varphi \left[a_0 + \frac{a_1 \left(T_{sk} + T_{en} \right)}{2} + a_2 v \right] S - \left(T_k - T_{en} \right) V_a \left(c_w \varphi G_{aw} + c_a \gamma_a \right)} \tag{12}$$

V enačbah od 1 do 12 simboli pomenijo: R_c – toplotni upor oblačila, m^2.h.°C/kJ; d_c – debelina oblačila, m; λ_c – koeficient toplotne prevodnosti oblačila, kJ/m.h.°C; R_a – toplotni upor mirne plasti zraka na površini oblačila; v – hitrost vetra, m/s; R_s – skupni toplotni upor oblačila in mirne plasti zraka na površini oblačila; λ – koeficient toplotne prevodnosti oblačila v katerihkoli pogojih; λ_0 – koeficient toplotne prevodnosti suhega

In Equations 1 to 12, the used symbols mean: R_c – thermal resistance of clothing, m^2.h.°C/kJ; d_c – thickness of clothing, m; λ_c – coefficient of heat conductivity of clothing, kJ/m.h.°C; R_a – thermal resistance of motionless air layer on clothing surface; v – velocity of wind, m/s; R_s – total thermal resistance of clothing and motionless air layer on clothing surface; λ – coefficient of heat conductivity of clothing in any conditions; λ_0 – coefficient of heat conductivity of oblačila v standardni atmosferi v mirnem vremenu; k_T – smerni koeficient (k_T = 0,0025) krivulje odvisnosti koeficienta toplotne prevodnosti od temperature oblačila; k_w – smerni koeficient krivulje odvisnosti koeficienta toplotne prevodnosti oblačila od količine vode v % v oblačilu (k_w = 0,04); ΔG_c – povečanje mase oblačila v % zaradi povečanja količine vode v oblačilu – odstotek vode v oblačilu; b – koeficient, ki ponazarja tesnjenje oblačila (pri oblačilu, ki dobro tesni, kot je v našem primeru, ima koeficient b vrednost 1), če oblačilo ne tesni, potem je b > 1; c_a – specifična toplota zraka (0,966 kJ/kg.°C); γ_a – gostota zraka (1,2 kg/m^3); V_a – volumenska hitrost pretoka zraka skozi oblačilo pri določeni hitrosti vetra, m^3/m^2.h; ΔQ_b – razlika med količino proizvedene toplote, ki ni uporabljena za delo mišic in notranjih organov, in izžarene toplote v okolje (v coni ugodja ΔQ_b = 0), kJ/m^2.h °C; c_b – specifična toplota telesa, kJ/kg.°C; G_b – teža telesa, kg; T_{av1} – povprečna temperatura telesa v coni ugodja (36,6 °C); S – površina kože, m^2; φ = (100 – RH)/100, kjer je RH relativna vlaga zraka izražena v %; T_{va2} – povprečna aktualna temperatura telesa, °C; T_{sk} – temperatura na površini kože, °C; T_{en} – temperatura okolja, °C; ΔR_{ti} – sprememba toplotnega upora plašča telesa glede na stanje v coni ugodja; c_w – specifična toplota izhlapevanja vode; a_0, a_1 *in* a_2 – koeficienti regresijske krivulje; V_a – količina izdihanega zraka v času opazovanja, m^3/h; T_{skc} – temperatura na površini kože v coni ugodja, °C; R_{s1} – skupni toplotni upor oblačila v coni ugodja; R_{s2} – skupni toplotni upor oblačila v aktualnih pogojih; T_k – temperatura jedra telesa, °C; G_{av} – količina vode v izdihanem zraku, gr/m^3.h; t – čas v urah, ki je potreben, da se doseže kritična temperatura podhlajevanja ali segrevanja telesa, oziroma čas, v katerem dosežemo vnaprej izbrano srednjo temperaturo telesa.

V enačbi 8 se toplota Q_1 nanaša na del proizvedene toplote v telesu, ki ne zajema toplote, porabljene za delo mišic in notranjih organov. Q_2 se nanaša na del toplote, ki jo oseba izžareva skozi površino kože in potem skozi površino oblačila neposredno v okolje v kateremkoli stanju organizma, kar pomeni tudi v območju ugodja ali pri pregrevanju oziroma podhlajanju organizma. Nekaj proizvedene toplote se porabi za izhlapevanje znoja (Q_3), nekaj pa pri dihanju (Q_4). Pri podhlajanju organizma se relativno malo toplote porabi za izhlapevanje znoja, ker se v tem stanju organizma pač izloča in izhlapeva zanemarljiva količina znoja. Pri pregrevanju organizma pa je izguba toplote zaradi izhlapevanja znoja bistvenega pomena za preprečevanje pregrevanja organizma in omogoča daljše delovanje v razmerah, ki pripeljejo do pregrevanja organizma. Zato bomo te izgube upoštevali pri pregrevanju.

Toplota Q_4, ki jo oseba oddaja med dihanjem, pa je odvisna od razlike temperature med jedrom telesa in okoljem, relativne vlage v okolju, vrste in intenzitete aktivnosti osebe oziroma števila vdihov in izdihov v enoti

dry clothing in standard atmosphere in still weather; k_T – heat conductivity coefficient/clothing temperature dependence curve coefficient (k_T = 0.0025); k_w – heat conductivity coefficient / % of humidity in clothing dependence curve coefficient (k_w = 0.04); ΔG_c – increase of clothing mass in % due to increase of water in clothing – percentage of water in clothing; b – coefficient illustrating tightening properties of clothing (if clothing tightens well as in our case coefficient b has value 1, if it does not tighten b > 1; c_a – specific air heat (0.966 kJ/kg.°C); γ_a – air density (1.2 kg/m^3); V_a – velocity of airflow through clothing at defined velocity of wind, m^3/m^2.h; ΔQ_b – difference between the amount of generated heat which is not consumed for muscles and internal organs functioning and the amount of emitted heat into the environment (in the zone of comfort ΔQ_b = 0), kJ/m^2.h °C; c_b – specific body heat, kJ/kg.°C; G_b – body mass, kg; T_{av1} – mean body temperature in the zone of comfort (36.6 °C); S – body superficies, m^2; φ = (100 – RH)/100, where RH is relative air humidity expressed in %; T_{va2} – mean real body temperature, °C; T_{sk} – temperature on skin superficies, °C; T_{en} – temperature of environment, °C; ΔR_{ti} - change of body superficies thermal resistance in dependence of state in the zone of comfort; c_w – specific water vapor heat; a_0, a_1 *in* a_2 – regression curves coefficients; V_a – amount of exhaled air during the observation time, m^3/h; T_{skc} – temperature on skin surface in the zone of comfort, °C; R_{s1} – total thermal resistance of clothing in the zone of comfort; R_{s2} – total thermal resistance of clothing in real conditions; T_k – body core temperature, °C; G_{av} – amount of water in exhaled air, gr/m^3.h; t – time in hours required to achieve critical temperature of body cooling down or overheating and the time in which a predefined mean body temperature is achieved, respectively.

In Equation 8, Q_1 refers to the fraction of the generated heat in the body, which does not include the heat needed for muscles and internal organs functioning. Q_2 refers to the fraction of the heat, which is emitted through the skin surface and clothing directly into the environment in any state of organism, including the zone of comfort and the process of overheating and cooling down. A certain amount of the generated heat is used for sweat evaporation (Q_3) and respiration (Q_4). In the process of cooling down, a relatively low amount of heat is used for sweat evaporation because in that state the organism excretes or evaporates only a negligible amount of sweat. In the process of warming up, however, the loss of heat due to sweat evaporation is extremely important for preventing overheating of the body and prolonging the tolerance time. These losses will be, therefore, considered in the process of overheating.

Heat Q_4, emitted by the person into the environment during respiration, depends on the difference between the body core temperature and the temperature of environment, relative humidity of environment, type and intensity of the performed activity, number of inhalations and exhalations in a unit časa in količine vdihnjenega zraka. Te izgube skrajšujejo čas doseganja kritičnega stanja med časom ohlajanja. Pri pregrevanju organizma pa podaljšujejo čas doseganja kritičnega stanja. Izgube toplote Q_3 bomo upoštevali le pri pregrevanju organizma opazovane osebe.

Proizvedeno toploto Q_1 lahko izmerimo oziroma vzamemo podatke iz literature. V kontaminiranem (strupenem) okolju opravlja oseba različna dela z različno intenziteto in pri tem proizvaja različne količine toplote v določenih časovnih presledkih. Vendar lahko uporabimo določeno srednjo vrednost, ki je najbolj verjetna glede na vrsto in intenziteto dela, ki ga opravlja opazovana oseba. V kontaminiranem okolju ne moremo neposredno meriti količine izžarjene toplote skozi površino kože, če nismo opremljeni s posebno laboratorijsko opremo. Seveda lahko simuliramo podobne razmere, kot jih bo imela oseba v kontaminiranem okolju.

Vsota izgub toplote (Q_2, Q_3 in Q_4) je lahko enaka količini proizvedene toplote (cona ugodja), večje (podhlajanje organizma) ali pa manjše od količine proizvedene toplote (pregrevanje organizma). V coni ugodja bomo v prvi aproksimaciji zanemarili Q_3 in eventualno tudi Q_4 in bomo predpostavili, da je termoizolacijska vrednost zaščitnega oblačila, ki ga ima oseba na sebi, enaka potrebni termoizolacijski vrednosti, da se ohrani cona ugodja v brezvetrju v suhem oblačilu.

V coni pregrevanja organizma ima toplota Q_3 pomembno vlogo. V tej coni ima pozitivno vlogo zmanjšanje termoizolacije plašča telesa in oblačila ter hitrost vetra. Pozitivno vlogo ima tudi toplota Q_4, vendar bi jo lahko zanemarili. V coni podhlajevanja pa ima pozitivno vlogo le povečanje termoizolacijske vrednosti plašča telesa. Zrak, ki ga vdihavamo, se zasiti z vodno paro in se segreje ali ohladi na temperaturo jedra telesa, T_k, kar je odvisno od temperature zraka, ki ga vdihavamo.

3.0 RAZPRAVA O TEORIJI

Enačba 12 je splošna rešitev za izračun časa (časa tolerance), v katerem lahko oseba brez poškodbe posameznih delov telesa opravlja določeno delo v posebnih razmerah, v katerih lahko pride do podhladitve organizma ali njegovega pregrevanja. ΔQ_b (enačba 6) je količina toplote, ki jo smemo dodatno izčrpati iz organizma, da se ta ohladi na kritično srednjo vrednost, na primer 30 °C, ali da se v organizmu ne nakopiči več dodatne toplote, kot je potrebno, da se srednja temperatura telesa dvigne na kritično vrednost, na primer 39 °C. Predpostavimo, da zaščitno oblačilo dobro tesni na odprtinah (konec rokava, pas, oba konca hlač, pas in spodnji del, ovratnik ipd.), sicer pa je zaščitno oblačilo prepustno za zrak in vodno paro. Strupene pline, če smo v kontaminirani (strupeni) coni, pa absorbira aktivno oglje v filtru maske in posebna aktivna plast (aktivirana grafitirana tkanina ipd.). Vse odprtine na

time and amount of the inhaled air. These losses shorten the time needed to reach the critical state during the cooling down process and extend it during the warming up process. Losses of heat Q_3 will be considered only in the process of overheating.

Heat Q_1 can be measured or taken from literature. In the contaminated (intoxicated) environment, a person performs different activities with different intensity and generates different amounts of heat in defined time intervals. Nevertheless, a certain mean value, which is the most probable with regard to the type and intensity of the performed work, can be used. In the contaminated environment, it is impossible to measure the quantity of the heat emitted through the skin surface directly without special laboratory equipment. It is possible, of course, to simulate the conditions similar to those in the contaminated area.

The sum of heat losses (Q_2, Q_3 and Q_4) can be the same as the amount of the generated heat (the zone of comfort), higher (cooling down) or lower (overheating). In the zone of comfort, the first approximation neglects Q_3 and possibly also Q_4 and presumes that the thermal resistance value of the person's protective clothing is the same as the thermal resistance value, which is necessary to preserve the zone of comfort in dry clothing and in still, non-windy weather.

In the zone of body overheating, heat Q_3 has an important role. In this zone, the decreased thermal insulation of the body covering and clothing as well as the velocity of wind have a positive effect. Although heat Q_4 has also a positive effect, it may be neglected. In the zone of body cooling down, only the increased thermal resistance value of the body covering has a positive effect. The inhaled air is saturated with water vapors and warms up or cools down to the body core temperature T_k, depending on the inhaled air temperature.

3.0 DISCUSSION ABOUT THEORY

Equation 12 is a general solution for calculating the period of time (the tolerance time) in which a person may, without damages of individual parts of the body, perform certain activities in extreme conditions in which overheating or cooling down of the body might occur. ΔQ_b (Equation 6) is the amount of the heat which may be additionally taken from the organism to enable it to cool down to the mean critical value, e.g. 30 °C, or to prevent accumulation of more heat than it is necessary for increasing the mean body temperature to the critical value, e.g. 39 °C. The presumption is that the protective clothing tightens firmly on openings (end of sleeves and trousers, waist, collar, etc.) otherwise it is considered air and water permeable. In a contaminated (intoxicated) area, toxic gases are absorbed by active carbon in the mask filter and a special active layer (activated graphitized fabric, etc.). If all openings in clothing are hermetically closed $b = 1$, if not oblačilu so hermetično zaprte. Zato je vrednost koeficienta $b = 1$. Če odprtine na oblačilu ne tesnijo, potem je $b > 1$. Problematično je ugotavljanje hitrosti izhlapevanja znoja. V prvi aproksimaciji smo predpostavili, da v coni ugodja in pri ohlajanju telesa lahko zanemarimo znojenje in izhlapevanje znoja. V coni segrevanja (kopičenje toplote v telesu) je znojenje intenzivno in se oblačilo prepoji z znojem. Zunanja površina oblačila je mokra.

Hitrost izhlapevanja v mirnem ozračju smo merili v standardni atmosferi (21 °C in 69 % RH).[11, 12] Hitrost izhlapevanja v odvisnosti od temperature in hitrosti vetra smo merili tako, da smo postopoma povečevali vrednosti temperature od 20 do 45 °C in hitrost vetra od 0 do 5 m/s (metoda ni standardizirana). Izbrali smo določene kote pihanja vetra na normalo površine oblačila. Pri merjenju smo simulirali oblačilo, prepojeno z znojem, in oblačilo, ki je na ovlaženi površini kože. Voda (znoj) hitreje izhlapeva s površine bombažne kot s površine volnene tkanine. Če je zunanja tkanina oblačila popolnoma premočena, ne prepušča zraka skozi pore v tkanini in zato ni dodatne površine (notranja površina por) za izhlapevanje znoja. Hitrosti izhlapevanja znoja ni mogoče enoznačno ugotoviti za vsa stanja in sestavo oblačila in ga je nujno eksperimentalno ugotoviti za vsak komplet oblačila posebej.

Dobro opremljenih laboratorijev za testiranje oblačil ni veliko. Storitve specializiranih, dobro opremljenih laboratorijev lahko uporabljajo predvsem vojska, policija ipd. Manjši uporabniki, na primer skupine alpinistov ipd., si kaj takega težko privoščijo. Poleg tega se pogosto spreminja sestava kompleta oblačila, če to ni predpisana in preizkušena uniforma. Vsaka sprememba bi zahtevala ponovitev celotnega preizkusa, kar je drago in neracionalno. Po drugi strani pa se lahko vprašamo, koliko je naša metoda zanesljiva. Preverjali smo zanesljivost metode glede vpliva hitrosti vetra na termoizolacijo oblačila. Upoštevali smo rezultate meritev spremembe termoizolacije polarne uniforme glede na hitrost vetra.[2] Izredno velik je vpliv hitrosti vetra na skupni toplotni upor oblačila, saj se je ta zmanjšal za več kot 60 % pri hitrosti vetra 10,7 m/s v primerjavi z vrednostjo pri hitrosti vetra 1,3 m/s. Iz zgornje primerjave se da sklepati, da je naša metoda vsaj delno verificirana, saj je vpliv hitrosti vetra parameter, ki ga je najteže vrednotiti glede na njegov vpliv na skupni toplotni upor.

Parametre, ki so potrebni za izračun časa tolerance z enačbo 12, lako izmerimo s pomočjo nekaj osnovnih laboratorijskih aparatov, kot so: aparat za ugotavljanje koeficienta toplotne prevodnosti, porozimeter (merilo hitrosti vetra), merilo debeline oblačila, precizna tehtnica ipd.

V enačbi 12 so zajeti tako rekoč vsi parametri, ki pomembno vplivajo na toplotno ravnovesje v človekovem organizmu. Eni igrajo pomembno vlogo pri ohlajanju organizma, drugi pri pregrevanju le-tega; tretji so pomembni tako pri ohlajanju kot pri pregrevanju organizma.

$b > 1$. It is difficult to determine the rapidity of sweat evaporation. In the first approximation, it is supposed that in the zone of comfort and during body cooling down, perspiration and sweat evaporation may be neglected. In the zone of warming up (accumulation of heat), however, perspiration is intensive and clothing gets soaked with sweat. The outer surface of clothing becomes wet.

The rapidity of evaporation is measured in standard atmosphere (21 °C and 69 % RH)[11, 12]. The rapidity of evaporation in dependence of temperature and velocity of wind is measured by gradually increasing the values of temperature from 20 to 45 °C and velocity of wind from 0 to 5 m/s (the method is not standardized). Several angles of wind blowing are chosen. The simulations of clothing saturated with sweat and clothing on the person's wet skin surface are used. Water (sweat) evaporates faster from a cotton fabric surface 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. The rapidity of sweat evaporation cannot be determined generally for all states and all compositions of clothing but should be determined experimentally for each set of clothing separately.

Well-equipped laboratory for testing clothing are not abundant. The services of specialized well-equipped laboratories are available first of all, to the army, police, etc. Smaller users like groups of alpinists cannot afford them. Besides, the composition of a set of clothing, unless a uniform is directed and tested, changes frequently and each such change would require repetition of the entire testing procedure, which would be expensive and unreasonable. On the other hand, the question about reliability of our method arises. The reliability of the method with respect to the effect of the velocity of wind on the thermal resistance value of clothing has been verified. The results obtained with measuring the change of the thermal resistance value of polar uniforms in dependence of the velocity of wind are used.[2] The influence of the velocity of wind on total thermal resistance of clothing is extremely high. At the velocity of wind 10.7 m/s, total thermal resistance of clothing decreases by more than 60% if compared with the value at the velocity of wind 1.3 m/s. The above comparison at least partly verifies our method. Namely, the influence of the velocity of wind is a parameter, which is the most difficult to be evaluated.

Parameters, which are needed in order to calculate the tolerance time by using Equation 12, can be measured with few basic laboratory devices, such as: device for determining heat conductivity coefficient, porosimeter, wind speed meter, clothing thickness meter, precision scales, etc.

Equation 12 encompasses practically all parameters, which significantly influence thermal balance in a human body. Some of them play important role in the body cooling down, the others in its warming up and there are also parameters, which are important in both processes. Therefore, there is no uniform use of Equation 12. When Equation 12 is used, the state of the body – overheating or cooling down – has to be

Zato ni enovite uporabe enačbe 12. Pri njeni uporabi moramo upoštevati stanje telesa – pregrevanje ali ohlajanje. Pa tudi nekateri parametri imajo dvojno vlogo. Pri pregrevanju organizma imata znojenje in premočenje oblačila pozitivno vlogo – hlajenje organizma. Pri tem se predvideva, da vsaj del izločenega znoja izhlapi. Hitrost vetra pospešuje izhlapevanje znoja in s tem tudi ohlajanje pregretega organizma človeka. Če pa je organizem v stanju ohlajanja, imata znojenje in hitrost vetra negativen vpliv – pospešujeta hitrost ohlajanja telesa subjekta.

4.0 PRIMER UPORABNOSTI ENAČBE 12 ZA IZRAČUN ČASA TOLERANCE

4.1 Definiranje kompleta oblačila

V vsakdanjem življenju lahko spreminjamo komplet po potrebi. Če je njegova termoizolacija prevelika za dane razmere (pregrevanje organizma), določene dele odložimo, s čimer zmanjšamo skupno vrednost termoizolacije in lahko ohranimo organizem na temperaturi ugodja (ravnovesje med izgubo in proizvodnjo toplote v območju ugodja). Če je termoizolacijska vrednost kompleta oblačila v danih razmerah premajhna – izguba toplote je večja od proizvodnje (hlajenje organizma), dodamo kakšno plast kompleta. Če te možnosti nimamo, se pred podhladitvijo branimo s povečanjem proizvodnje toplote (povečana intenziteta aktivnosti). Ta obramba pred podhladitvijo ima svoje meje. Organizem se utrudi, volja do življenja slabi in je včasih zaradi podhladitve organizma končni rezultat smrt.

V življenju se lahko zgodi, da v danih razmerah ne moremo spreminjati sestave kompleta. To velja zlasti za gasilce, potapljače, reševalce pri nesrečah v kemičnih tovarnah in ko imamo opravka s strupenimi snovmi (tekočinami in predvsem s plini) v vojnem času, ko gredo reševalci zavestno v kontaminirano področje ipd.

Za ilustracijo takih problemov bomo obravnavali komplet zaščitnega oblačila [13], ki je primeren za uporabo v strupeni atmosferi. Sem sodijo uporaba plinske maske, neprepustnih obuval (gumijastih škornjev ipd.), zaščitnih rokavic idr. Šivi oblačil morajo biti izdelani tako, da strupeni plini nimajo neposredne možnosti stika s površino kože. Enako velja tudi za vse odprtine na oblačilu. Dobro je tudi, da je tako oblačilo hidrofobno ali celo oleofobno, če atmosfera vsebuje razpršene tekoče delce strupenih snovi. To je še zlasti pomembno pri obrambi pred tako imenovanimi bojnimi strupi, ki jih v tekočem ali plinastem stanju absorbira površina kože in hromijo živčni sistem. Enako velja tudi za številne druge izdelke kemične industrije. Saj lahko zelo pogosto beremo o ladjah, ki jih nihče noče sprejeti v svoja pristanišča, ker so natovorjene z zelo strupenimi odpadki.

Naš namen ni študij potrebnih lastnosti zaščitnih oblačil, marveč ugotavljanje možnosti za izračun časa

considered. Furthermore, there are few parameters, which have a double role. For example: in the process of body overheating, sweating and wetting of clothing have a positive effect – they cool down a body. It is supposed that at least a fraction of the emitted sweat evaporates. The velocity of wind accelerates evaporation of sweat and, consequently, the process of the overheated body cooling down. However, in the process of body cooling down, sweating and the velocity of wind have a negative effect – they accelerate the process of body cooling down.

4.0 EXAMPLE OF APPLICABILITY OF EQUATION 12 FOR THE CALCULATION TIME OF TOLERANCE

4.1 Definition of Set of Clothing

In everyday life, a set of clothing can be changed as necessary. If its thermal insulation is too high for given conditions (body overheating), individual parts of clothing can be discarded. In this way, total thermal resistance value is reduced and the temperature, which is comfortable to a body, is preserved (the balance between heat loss and heat generation in the zone of comfort). If the thermal resistance value of the set of clothing is too low in given conditions – heat loss is higher than heat generation (body cooling), a layer of clothing can be added. If there is no such possibility, the increase of heat generation (increased intensity of activity) can be a solution. However, such solution has its limits. A body gets tired, vitality is fading and sometimes death might occur as the ultimate result of cooling down.

There are situations when it is not possible to change the composition of the set of clothing. This is the case with firemen, divers, rescuers (accidents in chemical plants and contact with toxic liquids and gases in war time) who consciously enter a contaminated area, etc.

In order to illustrate such problems, a set of protective clothing [13], suitable for use in a contaminated atmosphere will be investigated. Such set contains a gas mask, impermeable footwear (rubber boots, etc.), protective gloves, etc. The seams and openings of clothing should not allow a direct contact of gases with the skin. It is also advantageous that such clothing is hydrophobic or even oleophobic, if the atmosphere contains dispersed liquid particles of toxic substances. This is particularly important in defense from the so-called war poisons which are absorbed through the skin surface in liquid or gaseous state and which have a paralyzing effect on nerve system. The same applies to many other products of chemical industry. We can frequently read about ships, which are not allowed to enter ports due to being loaded with very toxic wastes.

Our intention is not to study the required properties of protective clothing but to identify the possibilities of calculatolerance, v katerem uporabnik določenega oblačila lahko opravlja določeno aktivnost pod določenimi pogoji, ne da bi pri tem dobil resnejše telesne in morebitne duševne okvare.

4.2 Komplet oblačila in njegove lastnosti

Analizirali bomo možnost za ugotovitev oziroma izračun časa tolerance pri uporabi kompleta. Obravnavali bomo le del kompleta, ki pokriva trup telesa. Pri tem bomo predpostavili, da so okončine, vrat in glava enako termoizolirane kot trup glede hitrosti hlajenja in pregrevanja. Sicer pa je obravnava glave, vratu in okončin, posebno še pesti in stopal na rokah in nogah, izjemno zahtevna.

Zaščitno oblačilo sestoji iz prekrivne tkanine, grafitirane tkanine (oksidirana in aktivirana tkanina, ki je izdelana iz PAN multifilamentne preje, ki absorbira strupene pline oziroma tekočine) in podloge.

Preglednica 1: Vrednosti koeficientov toplotne prevodnosti in vsebine vlage v posameznih plasteh v standardni atmosferi in debelina posameznih plasti

Plast oblačila	Debelina, mm	λ, kJ/m.h.°C	Vsebina vlage, %
Prekrivna tkanina	0,35	0,1234	5,1
Grafitirana tkanina	0,87*	0,1000*	1,0*
Podloga	0,41	0,7751	6,1

* Verjetne vrednosti, niso merjene. Vrednosti v tej preglednici potrebujemo za izračun toplotnega upora oblačila.

Preglednica 2: Vrednosti nekaterih pomembnejših parametrov poroznosti posameznih plasti oblačila [3]

Plast oblačila	Parametri poroznosti				
	A	*b*	*r*	D_{max}, µm	D_s, µm
Prekrivna tkanina	0,3815	0,768	0,999	97	21,6
Grafitirana tkanina	1,1826*	0,683*	0,988*	267*	85,4*
Podloga	0,4942	0,779	0,993	141	29,1

Parametri poroznosti v preglednici 2 pomenijo: *A* in *b* – koeficient in eksponent (enačba 14), *r* – koeficient korelacije (enačba 14), D_{max} – maksimalni hidravlični premer pore v obravnavani tkanini, D_s – srednji hidravlični premer por

* Predpostavili smo, da je poroznost grafitirane tkanine približno enaka poroznosti pene, ki je bila impregnirana z aktivnim ogljem in je bila del kompleta. Parametrov kakovosti grafitirane tkanine nismo merili. Predpostavili smo, da je debelina 0,87 mm (pena 2 mm) in da ima enako vrednost koeficienta toplotne provodnosti kot pena. Tako pena kot tudi vlaknovina z naneseno plastjo aktivnega oglja nista moderni rešitvi. Tukaj gre predvsem za ilustracijo možnosti rešitve problema ugotavljanja časa tolerance.

ting the tolerance time, i.e. the period of time in which a wearer of such protective clothing can continue to perform a certain activity in certain conditions without incurring any serious physical or even mental injury.

4.2 Set of Clothing and its Properties

The possibilities of defining or calculating the tolerance time when the set of clothing is used are going to be analyzed. Only the part of the set of clothing, which covers torso, will be dealt with. Extremities, neck and head are supposed to be identically thermally insulated as torso in terms of the rapidity of cooling and heating.

Protective clothing is composed of a covering fabric, a graphitized fabric (oxidized and activated fabric made from PAN multifilment yarn, which absorbs toxic gases and liquids) and a lining.

Table 1: Values of heat conductivity coefficients and percentage of humidity in individual layers in standard atmosphere and thickness of individual layers

Layer of Clothing	Thickness, mm	λ, kJ/m.h.°C	Percentage of humidity, %
Covering fabric	0,35	0,1234	5,1
Graphitized fabric	0,87*	0,1000*	1,0*
Lining	0,41	0,7751	6,1

* assessed values (not measured). The above values are needed to calculate thermal resistance of clothing.

Table 2: Values of some more important porosity parameters of individual layers of clothing

Layer of Clothing	Porosity Parameters				
	A	*b*	*r*	D_{max}, µm	D_s, µm
Covering fabric	0,3815	0,768	0,999	97	21,6
Graphitized fabric	1,1826*	0,683*	0,988*	267*	85,4*
Lining	0,4942	0,779	0,993	141	29,1

The parameters of porosity in Table 2 mean: *A* and *b* – coefficient and exponent (Equation 14), *r* – correlation coefficient (Equation 14), D_{max} – maximum hydraulic diameter of pore in the investigated fabric, D_s – mean hydraulic diameter of pore

* it is supposed that the porosity of a graphitized fabric is approximately the same as the porosity of foam impregnated with active carbon which is a part of the set of clothing. The parameters of graphitized fabrics were not measured. It is supposed that the thickness is 0.87 mm (foam 2 mm) and the value of heat conductivity coefficient the same as that of foam. Neither foam nor nonwovens coated with active carbon are not modern solutions. Here, the focus is on illustration possibility of solving of the problem of defining the tolerance time.

Za realno analizo sistema je zelo pomembna poroznost kompleta. To velja tako za dve ekstremni stanji (pregrevanje in podhlajanje), kakor tudi za stanje ugodja. S poroznostjo je v precejšnji meri povezan upor prevajanju pare skozi oblačilo, kar je pomembno pri pregrevanju organizma. Pri podhlajanju organizma, posebno če piha veter, prevelika poroznost pospešuje hitrost ohlajanja organizma. Tudi ni zanemarljiva velikost por. Pri enaki volumenski hitrosti pretoka pod enakim tlakom je lahko odprta površina za pretok sestavljena iz velikega števila por, ki imajo majhen povprečni hidravlični premer, ali pa iz manjšega števila por, ki imajo relativno velik povprečni hidravlični premer por. Take možnosti pa ne smeno zanemariti. Skozi pore, ki imajo velik hidravlični premer, laže prodirajo strupeni plini in strupene tekočine. Lahko se zgodi, da skozi poro »pade« drobna kaplja strupene snovi. Parametre poroznosti lahko ugotovimo s pomočjo metode za ugotavljanje števila, velikosti in porazdelitve por v ploskih tekstilijah.[3]

4.3 Uporabnik oblačila

Oblačilo je lahko namenjeno otrokom, odraslim ženskim ali odraslim moškim. Slednji (odrasli) se lahko razlikujejo ne samo po spolu, temveč tudi po višini, teži, površini kože, intenzivnosti presnove, občutljivosti na temperaturo ipd. Razumljivo je, da ne moremo obravnavati širše palete razlik med uporabniki. Zato bomo vpeljali pojem povprečnega uporabnika. Ta ima težo 70 kg in površino kože 1,8 m^2 in proizvaja naslednje količine toplote, odvisno od tega, kako težko delo opravlja: lahko delo – 417 kJ/m^2.h; zmerno težko delo – 697; težko delo – 1.047 in zelo težko delo – 1.397 kJ/m^2.h. Hoja 3 km/h – 420 kJ/m^2.h je enako lahkemu delu – 417 kJ/m^2.h. [4]

4.4 Stanje organizma uporabnika

Organizem uporabnika je v kateremkoli stanju med skrajno povprečnima temperaturama telesa, 30 oziroma 39 °C. Povprečne telesne temperature ni lahko izračunati, saj moramo upoštevati, da je na primer temperatura ugodja na površini čela ali prsi okrog 33 °C, medtem ko je temperatura ugodja na konicah prstov nog le okrog 24 °C. [14] Razlika je okrog 11 °C. Temperatura jedra telesa, ki zajema večji del mase telesa, je 37 °C.

Glede stalnosti temperature lahko človekovo telo ločimo na dva dela. Zunanja plast je plašč telesa, katerega temperatura ni stalna. Za plaščem je jedro telesa, ki ima stalno temperaturo. Seveda se tudi temperatura notranjosti telesa spreminja in je v izjemnih razmerah višja ali nižja od 37 °C. Temperaturni gradient plašča je približno 3 °C/cm. To pomeni, da se temperatura telesa povečuje, ko gremo od površine telesa proti njegovi

Porosity of the set of clothing is very important for a reliable analysis of the system. This applies to both extreme states (overheating and cooling down) as well as to the state of comfort. Porosity is in close relation with the resistance of clothing to vapor transmission, which is important in the conditions of body overheating. In the conditions of body cooling down, particularly if wind is blowing, too high porosity accelerates the rapidity of body cooling down. The size of pores is not negligible. With the same volume flow velocity under the same pressure, the open surface for flow can be made up of a large number of pores with a small mean hydraulic diameter or from a small number of pores with a relatively large mean hydraulic diameter. This factor should not be neglected. Toxic gases and liquids easily penetrate through pores, which have a large hydraulic diameter. It can happen that a droplet of a toxic substance falls through a pore. Porosity parameters can be identified by using the method of determining the number, size and distribution of pores in flat textiles.[3]

4.3 User of Clothing

Clothing can be designed for children, women and men who differ in height, weight, skin surface, metabolism intensity, heat sensitivity, etc. It is impossible to include such a wide range of differences in the investigation. That is why a concept of an average user has been introduced. The average user weighing 70 kg with the skin surface 1.8 m^2 generates the following amounts of heat (depending on the intensity of work): easy work – 417 kJ/m^2.h; moderate work – 697 kJ/m^2.h; hard work – 1.047 kJ/m^2.h and very hard work – 1.397 kJ/m^2. Walk 3 km/h – 420 kJ/m^2.h is comparable with easy work – 417 kJ/m^2.h [4].

4.4 Condition of User's Organism

In any state, the user's organism is between two extreme mean body temperatures, i.e. 30 and 39 °C. It is difficult to calculate the mean body temperature due to its variation. Thus, the temperature of comfort on forehead and chest is about 33 °C and on the toe tips only about 24 °C. [14] The difference is about 11 °C. The temperature of the body core which encompasses a bigger part of the body mass is 37 °C.

As to the temperature constancy, a human body can be divided into two parts. The outer layer is the body covering which doesn't have constant temperature. Behind the covering there is the body core, the temperature of which is constant as well. Of course, the temperature of the body core changes in extraordinary conditions and may be higher or lower than 37 °C. The temperature gradient of the body covering is about 3 °C/cm. That means that the body temperature increases from outside towards inside for 3 °C in 1 cm depth.

notranjosti za 3 °C na globini 1 cm. To ne velja za vse dele telesa, je le povprečna vrednost za telo v celoti. Ker je temperatura ugodja na prsih okrog 33 °C, bo debelina plašča, če upoštevamo temperaturni gradient, okrog 1,3 cm. Srednjo temperaturo telesa lahko izračunamo s pomočjo naslednje enačbe:

This is the mean value for the entire body and does not apply to all parts of the body. Since the temperature of comfort on chest is about 33 °C, the thickness of the covering will be about 1.3 cm if we consider the temperature gradient. The mean body temperature can be calculated by using the following equation:

$$T = aT_1 + bT_2 \tag{13}$$

kjer so: T – srednja temperatura telesa, T_1 – srednja temperatura plašča telesa, T_2 – temperatura jedra telesa, a – delež plašča telesa (0,2), b – delež jedra telesa (0,8). Ta deleža veljata v coni ugodja.

Če pa golo osebo potopimo v vodo v coni ugodja, se vrednosti obeh koeficientov spremenijo. Povprečna debelina plašča se poveča, izmerjeni in izračunani vrednosti pa sta a = 0,35 in b = 0,65 [8, 9]. Tako je zato, ker se v vodi organizem hitreje ohlaja in se meja stabilne temperature pomakne bolj v notranjost telesa. Ker se temperatura, na primer na površini konic prstov rok lahko zniža na temperaturo, ki je nižja kot 15 °C, je razlika met temperaturo jedra in povprečno temperaturo na površini kože precej večja kot v coni ugodja, čeprav se tudi temperatura jedra znižuje.

Glede prevajanja toplote se plašč telesa dobro prilagaja spremembi stanja telesa, saj se vrednosti njegovega koeficienta toplotne prevodnosti gibljejo v mejah od 3,023 kJ/m.h.°C (pregret organizem) do 0,3790 kJ/m.h.°C (podhlajen organizem). To pomeni, da se njegova termoizolacijska vrednost spremeni za okrog osemkrat. Če upoštevamo debelino plašča in vrednosti koeficienta toplotne prevodnosti, lahko z enačbo 1 izračunamo mejne vrednosti termoizolacije plašča telesa, ki so 0,0471 (organizem v coni ugodja) do 0,0729 m^2.h.°C/kJ (podhlajen organizem).[4]

Kaj praktično pomenijo omenjene vrednosti? Pri pregretosti organizma plašč telesa prevaja toploto bolj kot voda, kar je bistvenega pomena za hiter prehod toplote iz notranjosti telesa na njegovo površino in naprej v okolje. Pri prenosu toplote skozi plašč je takšno stanje posledica razširitve ožilja (kapilar) in pospešenega kroženja krvi s površine telesa proti notranjosti (ohlajena venozna kri) in iz notranjosti proti površini telesa (vroča arterijska kri).

Če je organizem podhlajen, se ožilje skrči, kroženje krvi se izredno upočasni, s čimer se tudi zelo poveča termoizolacijska vrednost plašča telesa. Ta je približno na ravni termoizolacije plutovine enake debeline. [10] Zaradi povečanja termoizolacijske vrednosti plašča in znižanja temperature na površini kože telesa pri hlajenju organizma se upočasni izguba toplote, s tem pa se povečajo možnosti za preživetje tudi tedaj, ko bi se sicer hitro znižala telesna temperatura, če bi plašč imel enako termoizolacijsko vrednost kot pri pregretem organizmu. Zgornja kritična temperatura v jedru telesa znaša okrog 39 °C, kritični utrip pa 180 utripov/min.

Where T is mean body temperature, T_1 – mean temperature of body covering, T_2 – temperature of body core, a – share of body covering (0.2), b – share of body core (0.8). These shares apply in the comfort zone.

But if a naked body is dipped into the water in the comfort zone, the values of both coefficients change. The mean thickness of the body covering increases and the measured and calculated values are a = 0.35 and b = 0.65 [8, 9]. In the water, the organism cools down quicker and the boundary of stable temperature moves deeper into the body.

Since for example the temperature on the hands finger tips can decrease to the temperature lower than 15 °C, the difference between the temperature of the body core and the mean temperature on the skin surface is substantially higher than in the zone of comfort despite the decrease of the body core temperature.

As to the heat conductivity, the body covering is adapting well to the change of the body state. The values of its heat conductivity coefficient range from 3.023 kJ/m.h.°C (overheated organism) to 0.3790 kJ/m.h.°C (cooling down organism). This means that its thermal resistance value changes for about eight times. By considering the thickness of the covering and the values of heat conductivity coefficients, boundary values of the body covering thermal insulation which range from 0.0471 (organism in the zone of comfort) to 0.0729 m^2.h.°C(kJ (cooling down organism) can be calculated by using Equation 1.[4]

What do these values mean practically? In the state of overheating, the body covering conducts heat better than water, which is of key importance for rapid transmission of heat from the body inside to its surface and into the environment. In the process of heat transfer through the body covering, such condition is the result of the veins (capillaries) swelling and the accelerated blood circulation from the body superficies towards the body core (cooled venous blood) and from the body core towards the body superficies (hot arterial blood).

If an organism is cooling down, veins shrink, blood circulation slows down and the thermal resistance value of the coating considerably increases and is almost the same as that of cork of the same thickness. [10] Due to the increase of the thermal resistance value of the body covering and the decrease of the temperature on the body superficies in the conditions of body cooling, loss of heat slows down and the possibilities of survival increase even in the conditions in which the body temperature would decrease quickly, if the covering had the same thermal resistance value as in the case of over-

Pri teh vrednostih lahko pride do toplotnega šoka. V teh razmerah se temperatura v notranjosti jedra in plašča izenačita. Razlika je neposredno na površini kože, s katere neposredno izhlapeva znoj. Ta je nekoliko nižja. Pri podhladitvi (brez upoštevanja stanja ušes, nosu in okončin ali njihovih delov – pesti in stopala, ki so lahko nepopravljivo poškodovani) se človek počuti zaspan, če se temperatura jedra telesa zniža pod 33 °C ter se upočasnita dihanje in srčni utrip. V takšnem stanju lahko zaradi podhladitve nastopi smrt.

Menijo, da se v organizmu ne bi smelo nakopičiti toplote za več kot 8,7 kJ/kg mase telesa. Omenjena količina toplote zviša telesno temperaturo na kritičnih 39 °C. Praktično pomemben je čas tolerance ali čas, ki je potreben, da v danih razmerah organizem pride v kritično območje (podhlajanje ali pregrevanje organizma). V tem času prehoda iz območja ugodja v območje kritičnega stanja organizma je mogoča bolj ali manj normalna dejavnost človeka.

Hitrost segrevanja ali ohlajanja organizma je odvisna tudi od vrednosti povprečne specifične toplote organizma. Ta znaša približno 3,5 kJ/kg °C. Zdaj so nam na voljo vsi parametri, ki so potrebni za izračun neravnovesja med proizvodnjo in izžarevanjem toplote. To lahko izračunamo z enačbo 6.

Iz enačbe 6 je razvidno, da ima ΔQ_b pri hlajenju negativno vrednost $T_{av1} > T_{av2}$ (telo oddaja toploto v okolje) in pozitivno vrednost pri segrevanju, $T_{av1} < T_{av2}$ (v telesu se akumulira energija predvsem iz lastne proizvodnje, lahko pa tudi delno na račun zunanjih obremenitev – gašenje požarov). Če pa je doseženo ravnovesje na ravni temperature ugodja, $T_{av1} = T_{av2}$ in $\Delta Q_b = 0$, ni neravnovesja pri izmenjavi energije (toplote).

heated organism. The upper critical temperature in the body core is about 39 °C and critical pulse rate 180 throbs per minute. These values may lead to heat shock. In such conditions, the temperature in the body core and the temperature of the body covering become equal. The difference is on the skin surface from which sweat directly evaporates. It is slightly lower. In the case of cooling down (without considering the condition of ears, nose and extremities and their parts – hands and feet, which can be irreparably damaged), a man feels sleepy if the body core temperature falls below 33 °C, breathing and heartbeat slow down and a man can die.

It is believed that the accumulated heat in the organism should not exceed 8.7 kJ/kg of body mass. This amount of heat raises the body temperature to critical 39 °C. The tolerance time or the time interval required by an organism to pass from the zone of comfort to the critical zone (cooling down or overheating) in given conditions is practically important. In this time interval, more or less normal activity can be performed.

The rapidity of the organism heating or cooling depends on the value of the body mean specific heat, which is approximately 3.5 kJ/kg.°C. Now, all parameters needed to calculate the imbalance between heat generation and heat emission are available. Equation 6 is used:

In Equation 6 it is evident that ΔQ_b has a negative value in the process of cooling $T_{av1} > T_{av2}$ (the body is emitting heat into the environment) and a positive value in the process of heating $T_{av1} < T_{av2}$ (energy accumulates in the body mostly from its own generation and possibly due to outside influences – fire extinguishing). If balance is obtained at the temperature of comfort level $T_{av1} = T_{av2}$ and $\Delta Q_b = 0$, there is no imbalance in the energy (heat) exchange.

4.5 Okolje

Stanje okolja je tisti dejavnik, ki narekuje vrsto in količino uporabljenega oblačila zaradi ohranjanja organizma v območju ugodja in zaščite pred zastrupitvijo, ognjem ipd. Že v našem podnebju so izjemno velike temperaturne razlike od + 39,2 °C v Mariboru (maksimum 15-letnega opazovanja) do –41,5 °C na Kredarici (2006). Veter zelo pogosto doseže hitrost 60 km/h (17 m/s) in več; letna količina padavin pa je od 600 mm do več kot 5000 mm. Kljub temu za vsa ta klimatska stanja lahko konstruiramo oblačila, ki uporabniku omogočajo normalno aktivnost tudi na prostem, razen v izjemnih primerih, ki pa v naših razmerah ne trajajo dolgo. Drugo vprašanje je zaščita uporabnika v posebnih (izjemnih) okoliščinah (strupena atmosfera, visoke temperature, ogenj idr.). V takšnih primerih moramo uporabiti posebna oblačila, katerih izdelava ni tako preprosta.

V mirnem in suhem ozračju (relativna vlaga 65-odstotna) je količina oblačil odvisna od temperature okolja in količine toplote, ki jo uporabnik oblačila izžareva

4.5 Environment

The state of environment is the factor, which dictates the type and quantity of clothing in order to keep the organism in the zone of comfort and to protect it from toxic substances, fire, etc. Already in our clime, extremely high temperature differences occur, i.e. from +39,2 °C in Maribor (15-year observation maximum) to –41.5 °C on Kredarica 2006. Wind frequently achieves or even exceeds the velocity 60 km/h (17 m/s). A yearly amount of precipitate is from 600 mm to more than 5000 mm. Despite such variations, it is possible to design clothing, which would enable normal activities in the open air, except in extraordinary cases, which never last long in our circumstances. Another issue is protection of the user of clothing in special (exceptional) circumstances (intoxicated atmosphere, high temperatures, fire, etc.) In such cases special clothing, which is not easy to manufacture, should be used.

In still and dry (relative humidity 65%) climatic conditions, the quantity of clothing depends on the environment temperature and on the amount of heat emitted by the user skozi površino kože. Na sliki 1 je ilustriran primer pri temperaturnem intervalu od – 20 do + 33 °C in količini izžarevane toplote od 420 do 1.400 kJ/m^2.h. Krivulja 1 kaže stanje, ko uporabnik opravlja lahko delo (420 kJ/m^2.h), krivulja 2 kaže zmerno težko delo (720 kJ/m^2.h), krivulja 3 težko delo 1.050 kJ/m^2.h) in krivulja 4 zelo težko delo, pri katerem uporabnik izžareva skozi površino kože 1.400 kJ/m^2.h. Kadar uporabnik oblačila opravlja težko delo, potrebuje najmanjšo količino oblačil. Vse štiri krivulje (premice) se stikajo na abscisi pri 33 °C. To je temperatura ugodja na površini kože. Temperatura sama po sebi vpliva na spremembo vrednosti koeficienta toplotne prevodnosti oblačila. Ta raste z zviševanjem temperature. Vendar so spremembe majhne, zato je trend spremembe glede na posledice spremembe temperature pozitiven (zaželen).

Vlaga (voda) zelo močno vpliva na spremembo vrednosti koeficienta toplotne prevodnosti. Naše raziskave [5] kažejo, da se v območju od 0 do 100 % vode v tkaninah spreminja (raste) vrednost koeficienta toplotne prevodnosti v povprečju 4 % za vsak povečani odstotek deleža vode v tkanini. Vpliv temperature in vlage smo upoštevali pri vrednosti λ v enačbi 4; vendar je upoštevanje vsebnosti vode pri pregrevanju izjemno težavno, ker na hitrost izhlapevanja vplivajo fiziološki koeficient zasičenja zraka, sam komplet glede na surovinsko sestavo, poroznost oblačila in hitrost vetra.

Če v enačbi 4 predpostavimo, da je $b = 1$, kar je upravičeno za zaščitno oblačilo, ki nima prostih odprtin, in vrednosti iz preglednic 1 in 2, lahko izračunamo R_s za komplet zaščitnega oblačila. Na sliki 2 je prikazana sprememba R_s v odvisnosti od hitrosti vetra. Pri tem smo upoštevali dejstvo, da enačba 2 velja za hitrost vetra 1 m/s in več. Vrednosti, ki so izračunane za hitrost vetra 1 m/s, veljajo kot vrednost v mirnem vremenu. V absolutno mirni atmosferi bi sicer lahko z ekstrapoliranjem krivulj na ordinato dobili večje vrednosti, kot so dejanske vrednosti, predvsem zaradi omejitve veljavnosti enačbe 2.

Poroznost lahko izračunamo z enačbo 14, če pri tem upoštevamo eksperimentalne rezultate v preglednici 2. Pri tem moramo upoštevati uporabljene enote. Parametra A in b v preglednici 2 se nanašata na prostorninsko hitrost pretoka, izraženega v cm^3/cm^2.s in tlaka v Pa, (enačba 14).

Kot je razvidno iz preglednice 2, je eksponent b večji kot 0,5. Za b dejansko velja naslednja omejitev: $0{,}5 \leq b \leq 1$. Čim gostejša je tkanina, tem večja je vrednost eksponenta b.

Prostorninsko (volumensko) hitrost dobimo, če linearno hitrost pretoka pomnožimo z odprto površino v tkanini, ki jo tvorijo pore med nitmi osnove in votka, oziroma volumenski pretok izračunamo s pomočjo naslednje enačbe:

through the skin. Figure 1 illustrates an example in the temperature interval from –20 to +33 °C and with the amount of emitted heat from 420 to 1400 kJ/m^2.h. Curve 1 shows the state when a user performs easy work (420 kJ/m2.h), curve 2 refers to moderate work (720 kJ/m^2.h), curve 3 to hard work (1050 kJ/m^2.h) and curve 4 to very hard work during which the user emits 1400 kJ/m^2.h through the skin surface. When a user of clothing works hard, he needs minimal quantity of clothing. All four curves (lines) join on abscissa at 33 °C. This is the temperature of comfort on the skin surface. The temperature itself has effect on the value of the clothing heat conductivity coefficient. The value increases with the increase of temperature. However, the changes are minimal, so that the trend of change is positive (desired) in view of the consequences of the temperature change.

Humidity (water) has a considerable effect on the change of the heat conductivity coefficient value. Our researches [5] show that within the range 0 – 100% of water in fabrics, this value changes by 4% on average for each increased percentage of water in fabric. The influence of temperature and humidity is considered in λ value in Equation 4. However, it is difficult to estimate the percentage of water during the process of overheating, because the rapidity of evaporation depends also on the air saturation physiological coefficient, material of clothing, porosity of clothing and the velocity of wind.

If $b = 1$ (protective clothing without any free openings) and the values from Tables 1 and 2 are used in Equation 4, R_s for the set of protective clothing can be calculated. Figure 1 shows the change of R_s in dependence of the velocity of wind. The fact that Equation 2 applies for the velocity of wind equal or higher than 1 m/s is taken into account. The values, which are calculated for the velocity of wind 1 m/s are considered the values in still weather. Otherwise, higher values than actual ones would be obtained in an absolutely still atmosphere by extrapolation of curves to ordinate, particularly due to limited validity of Equation 2.

Porosity can be calculated with Equation 5 provided that the experimental results in Table 2 are considered. It is important that the used units are taken into account. Parameters A and b in Table 2 refer to the volume flow rapidity expressed in cm^3/cm^2.s and water column pressure in Pa (Equation 14).

As can be seen in Table 2, exponent b is higher than 0.5. As already mentioned, the following limitation applies to b: $0.5 \leq b \leq 1$. Denser is the fabric, higher is the value of exponent b.

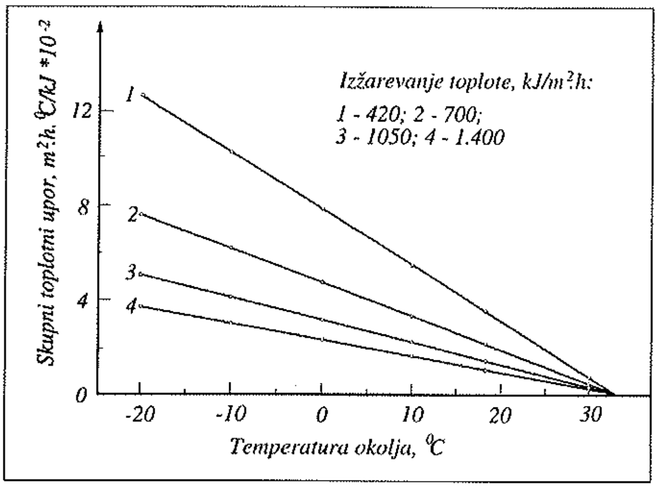
The volume rapidity is calculated by multiplying the flow linear velocity with the open surface in fabric, which is made up of pores between warp and weft. The volume flow is calculated by using the following equation:

$$V = Ah^b = Pah^b \quad (14)$$

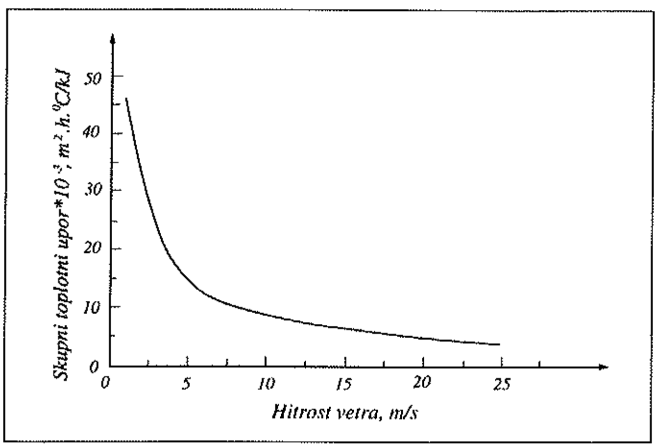
kjer so: V – volumenska hitrost pretoka zraka skozi oblačilo, A – koeficient regresijske krivulje, b – razlika tlakov, b – eksponent regresijske krivulje, P – odprta površina za pretok plinov, ab^b – linearna hitrost pretoka zraka.

Pri hitrosti vetra 1 m/s (3,6 km/h), ki jo jemljemo kot zgornjo mejno hitrost med stanjem mirne atmosfere in stanjem, ko začnemo upoštevati hitrost vetra, je prostorninska hitrost pretoka 9,4 m^3/m^2.h pri 5 m/s (18 km/h); 112 pri 10 m/s (36 km/h); 324 pri 15 m/s (54 km/h); 604 pri 20 m/s (72 km/h) in 939 pri 25 m/s (90 km/h). To so pretoki skozi zgornjo plast oblačila (prekrivna tkanina).

Poroznost oblačila je zelo velika, kar ugodno vpliva na hlajenje – izhlapevanje znoja, vendar ima pri nižjih temperaturah in pri vetrovnem vremenu negativne učinke. Pa ne samo na termoizolacijo, temveč tudi na filtracijo (tudi pri višjih temperaturah). Strupene hlape nese veter skozi oblačilo. S tem se obremenjuje filtracijska plast, ki se hitreje zasiti kot takrat, ko ni vetra. To lahko sklepamo iz količine zraka, ki gre skozi oblačilo pri določeni hitrosti vetra. Podoben učinek ima znoj, kjer absorpcijska plast, premočena z znojem, nima več takšne sposobnosti absorpcije kot v suhem stanju. Na sliki 2 je prikazana sprememba R_s v odvisnosti od hitrosti vetra. Drastično je zmanjšanje vrednosti toplotnega upora.



Slika 1: Odvisnost R_s od temperature in proizvedene toplote



Slika 2: Odvisnost R_s kompleta zaščitnega oblačila od hitrosti vetra

where V is air volume flow rapidity through clothing, A is regression curve coefficient, b is pressures difference, b is regression curve exponent, P is open surface for gases flow, ab^b is air flow linear rapidity.

At the velocity of wind 1 m/s (3.6 km/h), which is considered to be the upper boundary velocity between the condition of still atmosphere and the condition of wind blowing, the flow volume rapidity is 9.4 m^3/m^2.h at 5 m/s (18 km/h), 112 at 10 m/s (36 km/h), 324 at 15 m/s (54 km/h), 604 at 20 m/s (72 km/h) and 939 at 25 m/s (90 km/h) through the top layer of clothing (covering fabric).

Porosity of clothing is very high, which has a favorable effect on body cooling – sweat evaporation, however, at lower temperatures and in windy weather, it has negative effect not only on thermal insulation but also on filtration (also at higher temperatures). Toxic vapors, which are transmitted through clothing by the wind deteriorate the capacity of the filtration layer. This can be concluded from the amount of air, which passes through clothing at certain velocity of wind. Sweat has the same effect – the absorption layer soaked with sweat has lower absorption capability than a dry layer. Figure 2 illustrates the change of R_s in dependence of the velocity of wind. The values of thermal resistance have dropped drastically.

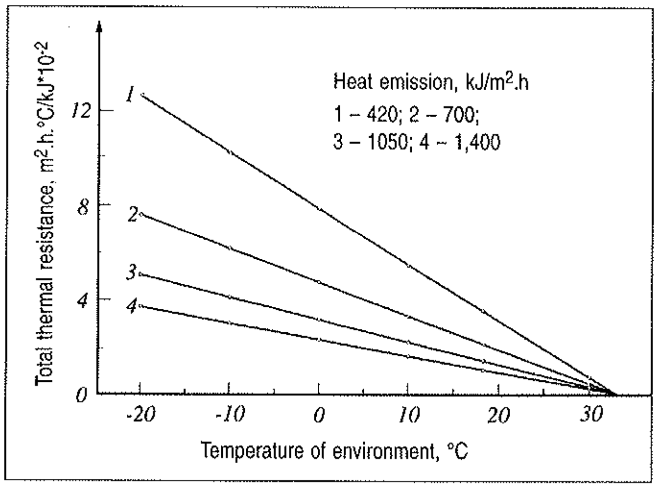


Figure 1: Dependence of R_s on temperature and generated heat

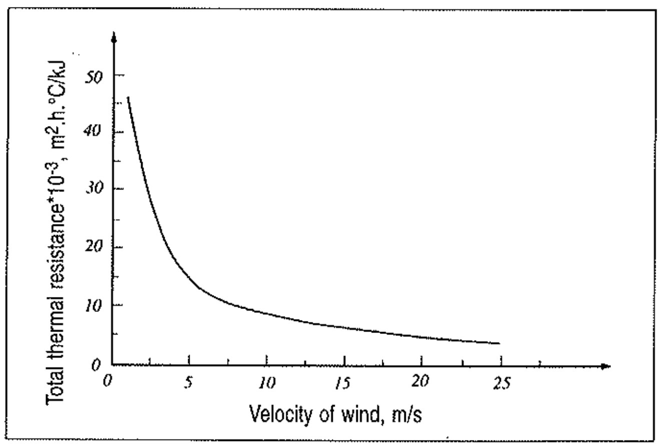


Figure 2: Dependence of R_s of set of clothing on velocity of wind

4.6 Ohlajanje organizma

Povprečna temperatura organizma se lahko zniža do 30 °C in več. Pri tem je temperatura na površini kože precej nižja – vsaj 28 °C ali še manj na prsih. Kot je razvidno iz preglednice 3, ki se nanaša na površino čela, je v takšnem stanju organizma subjektivni občutek boleč – zelo mrzel. Če se organizem ohlaja še naprej, bolečine postopoma prenehajo, telo otrpne, zmanjša se število srčnih utripov na enoto časa, človek postaja zaspan in če se organizem še naprej ohlaja, nastopi smrt. Vsekakor je zanimivo in tudi koristno ugotoviti čas tolerance, v katerem smemo uporabnika oblačila izpostaviti zunanjim vplivom, preden nastopijo resnejše okvare na posameznih delih telesa in predvsem na okončinah. Znižanje temperature jedra telesa pod 33 °C pa pomeni izjemno nevarnost. Zato bomo 30 °C **upoštevali** kot **arbitrarno** spodnjo povprečno mejno temperaturo organizma, pri kateri so še mogoče določene aktivnosti subjekta.

Preglednica 3: Odvisnost počutja osebe in vlažnosti kože od temperaturena površini čela [6]

Temperatura kože, °C	Subjektivno počutje osebe	Odstotek kože, ki je prekrit z znojem
28,0–29,9	zelo mrzlo	10–18
30,0–32,1	mrzlo	10–20
32,2–33,2	prijetno	12–25
33,3–34,3	toplo	15–30
34,4–35,5	vroče	30–90
35,6–36,6	zelo vroče	100

V območju ugodja je vrednost temperaturnega gradienta 3 °C/cm in povprečna debelina plašča telesa (koža in podkožno tkivo) okoli 1,3 cm. Na spodnji mejni temperaturi ohladitve pa se stanje spremeni, saj se precej zmanjša vrednost koeficienta toplotne prevodnosti plašča. Ta vrednost je primerljiva z vrednostjo koeficienta toplotne prevodnosti plutovine. Plašč ima najvišjo termoizolacijsko vrednost, ko tako rekoč preneha krožiti kri v njem. To je stanje, ki pomeni tudi nevarnost odmiranja tkiva, če traja dovolj dolgo. Nekateri poskusi [7] so pokazali, da je mogoče v 40 minutah znižati temperaturo prstov roke na nekaj stopinj nad 0 °C (temperatura na vrhu mezinca se je znižala celo na + 1 °C) brez vidnih poškodb tkiva. Sicer pa se zmanjša gibljivost prstov rok, če temperatura na konicah prstov pade pod 15 °C.

Pri ohlajanju telo proizvede določeno količino toplote Q_1 in odda v okolje toploto Q_2, Q_3 in Q_4 Pri tem je vsota $Q_2 + Q_3 + Q_4 > Q_1$. Dejanski primanjkljaj energije ΔQ_b, kJ/m^2.h lahko izračunamo z enačbo 7. Pri ohlajanju organizma lahko zanemarimo Q_3, ker je količina toplote, ki se porabi za izhlapevanje znoja, zanemarljiva v primerjavi s toploto Q_2, ki se izžareva skozi površino kože in skozi oblačilo v okolje.

4.6 Cooling Down of Organism

The mean body temperature can drop to 30 °C and lower. The temperature on the skin surface is significantly lower – at least 28 °C or even lower on the chest surface. In such condition, as can be seen from Table 1, which refers to the surface of forehead, a painful feeling of cold overflows the organism. If the process of cooling is going on, pains slowly stop, a body numbs, the number of heartbeats per time unit decreases, a person becomes sleepy and finally dies if the process of cooling still continues. In any case, it is interesting and useful to define the tolerance time, i.e. the time during which a user of clothing may be exposed to external influences without suffering serious damages on individual parts of the body, particularly on extremities. However, the decrease of the body core temperature under 33 °C represents a serious threat. Thus, this temperature of 30 °C will be considered as arbitrary the bottom boundary mean body temperature, which still allows certain activities of a subject.

Table 3: Dependence of feeling and skin moisture of the temperature on surface of forehead [6]

Skin Temperature on forehead, °C	Subjective Feeling of a Person	Percentage of Skin Covered with Sweat
28,0–29,9	Very cold	10–18
30,0–32,1	Cold	10–20
32,2–33,2	Comfortable	12–25
33,3–34,3	Warm	15–30
34,4–35,5	Hot	30–90
35,6–36,6	Very hot	100

In the zone of comfort, the value of the temperature gradient is 3 °C/cm and the mean thickness of the body covering (skin and subcutaneous tissue) 1.3 cm. At the bottom boundary body temperature of cooling, the condition changes as the value of the heat conductivity coefficient of the covering significantly decreases. This value is comparable with the value of the heat conductivity coefficient of cork. The body covering has the highest thermal resistance value when blood practically ceases to circulate in it. This is the state which might lead to the danger of dyeing of tissue if it lasts long enough. Certain experiments [7] have shown that it is possible to reduce the temperature of fingers to few degrees above 0 °C in 40 minutes (the temperature on a little finger tip decreases to +1 °C) without any visible damage of tissue. Otherwise, movable of fingers diminishes if the temperature on finger tips falls under 15 °C.

In the process of cooling, a human body generates heat Q_1 and emits heat Q_2, Q_3 and Q_4 into the environment. The sum of $Q_2 + Q_3 + Q_4$ is higher than Q_1. The actual deficit of energy ΔQ_b, kJ/m^2.h can be calculated by using Equation 7. In the process of cooling, Q_3 can be neglected because the amount of the heat consumed for sweat evaporation is negligible in comparison with the amount of heat Q_2, which is emitted through the skin surface and clothing into the environment.

Toploto Q_4 pa bi verjetno v nekaterih primerih težko zanemarili, vsaj pri nizkih temperaturah. Kot je razvidno iz enačbe 11, je ta sorazmerna z vsakokratno razliko temperature v jedru telesa in temperaturo okolja. V coni ugodja je temperatura jedra telesa 37 °C. Ta se lahko zniža do 33 °C in pri podhladitvi celo bolj. Pri tem ni nujno, da je temperatura okolja pod 0 °C. Količina izdihanega zraka, ki ima enako temperaturo kot jedro telesa, je odvisna od števila izdihov in količine zraka pri enem izdihu. Število vdihov in izdihov pa je odvisno od vrste in intenzitete aktivnosti osebe. Predpostavljamo, da je zrak, ki ga izdihavamo, nasičen. Če izdihamo 15 litrov zraka v minuti ali 900 litrov na uro in je razlika med temperaturo jedra telesa in temperaturo okolja 40 °C, specifična toplota zraka 0,966 kJ/kg.°C in specifična teža zraka 1,2 kg/m^3, bomo porabili za zagrevanje zraka okrog 42 kJ/h. Človek v večini primerov v eni uri izdihne od 10 do 14 gramov vode, kar pomeni, da toliko vode tudi izhlapi. Lahko predpostavimo, da je v vdihanem zraku okrog 70 % vlage v parni fazi. To moramo upoštevati pri računanju toplote, ki je potrebna za izhlapevanje izdihanega zraka. Ta ni za okrog 70 % manjša, kot smo izračunali za celotno količino izdihanega zraka. Moramo upoštevati dejstvo, da se vdihani zrek segreje na temperaturo pljuč. Če zrak, ki ima temperaturo 0 °C in 70 % relativne vlage ter parcialni tlak vodne pare 425 Pa in ga segrejemo na temperaturo pljuč, na primer na 33 °C, bo njegova relativna vlaga padla pod 10 %. To bi pomenilo le nekaj kJ/h manj porabe toplote. Skupaj torej okrog 40 kJ/h. Dejansko moramo nekoliko modificirati realen izračun izgube toplote zaradi segrevanja vdihnjenega zraka. Računamo le razliko, ki jo dobimo, če telo ohladimo v mirnem vremenu na nižjo temperaturo, kot je temperatura ugodja.

Če predpostavimo, da se telo enakomerno ohlaja in je temperatura okolja v coni ugodja 15 °C (naš komplet daje to vrednost), bomo upoštevali razliko med to temperaturo in temperaturo okolja, pri kateri se jedro telesa ohladi na 33 °C, če je ta nižja od 15 °C v mirnem vremenu brez vetra. Računamo le s polovično vrednostjo razlike. Če računamo čas tolerance pri –5 °C, potem ne računamo z razliko 20 °C, ampak le z 10 °C. Dodatna izguba toplote zaradi segrevanja vdihanega zraka bo le okrog 10 kJ/h. To bi bilo le 1 % od 1.000 kJ/h ali 1,7 % pri izgubi toplote 600 kJ/h skozi površino kože. Prazvprav nimamo dodatne izgube toplote zaradi izhlapele vode v izdihanem zraku glede na izgube v coni ugodja. Iz tega primera izhaja, da pri podhlajanju osebe lahko zanemarimo dodatne izgube toplote zaradi segrevanja vdihanega zraka. To pa velja le v primeru, če temperature niso skrajno nizke oziroma če se kritična temperatura, pri kateri se temperatura telesa zniža na kritično vrednost, preveč ne razlikuje od temperature ugodja za opazovane razmere, vključno z oblačilom (ni spremembe stanja oblačila).

In some cases, at least at low temperatures, heat Q_4 could be hardly neglected. As can be seen in Equation 11, heat Q_4 is proportional to every difference between the temperature in the body core and that of the environment. In the zone of comfort, the temperature of the body core is 37 °C but it can decrease to 33 °C or even lower in the case of cooling down. It is not necessary that the temperature of environment is under 0 °C. The amount of the exhaled air, which has the same temperature as the body core, depends on the number of breaths and the amount of the exhaled air in one breath. The number of breaths out and breaths in depends on the type and intensity of the subject's activity. The air, which is breathed out, is supposed to be saturated. If 15 liters of air is breathed out per minute, i.e. 900 liters per hour, if the difference between the temperature of the body core and the temperature of environment is 40 °C and if specific heat of air is 0.966 kJ/kg. °C and specific mass of air 1.2 kg/m^3, approximately 42 kJ/h will be used for heating the air. In most cases, a man exhales 10 to 14 grams of water in 1 hour, which means that this amount of water evaporates. It can be assumed that there is about 70% of humidity in the vapour phase in the inhaled air. This should be considered when the amount of the heat required for evaporation of the exhaled air is calculated. It is not by about 70% lower as was calculated for the total amount of the exhaled air. The fact is that the inhaled air warms up to the the temperature of lungs. If the air which has the temperature 0 °C and 70 % of relative humidity and the water vapour partial pressure 425 Pa is warmed up to the temperature of lungs, e.g. 33 °C, its relative humidity will fall below 10%. This would mean lower consumption of heat for only few kJ/h. This is totally about 40 kJ/h. In fact, a real calculation of the loss of heat should be slightly modified due to heating of the inhaled air. Only the difference, which is obtained if a human body is cooled down in still weather to a temperature lower than the temperature of comfort, is calculated.

Supposing that a human body is cooling down evenly and that the temperature in the zone of comfort is 15 °C (our set of clothing provides such value), the difference between this temperature and the temperature of environment, at which the body core cools down to 33 °C, if it is lower than 15 °C in still non-windy weather, will be considered. In calculations, only half value of this difference will be used. If the tolerance time is calculated at –5 °C, it is not the difference of 20 °C, which will be taken into account but only half of this value, i.e. 10 °C. Additional loss of heat as a result of the inhaled air heating will be only about 10 kJ/h. This would be only 1% of 1,000 kJ/h or 1.7% at the heat loss 600 kJ/h through the skin surface. There is practically no additional loss of heat due to evaporated water in the exhaled air in comparison with the loss in the zone of comfort. This example shows that in the process of cooling down, additional losses of heat due to the inhaled air heating can be neglected. However, this applies only if the temperature is not extremely low or if the critical temperature, at which the body temperature falls to the critical value

Ne moremo pa zanemariti spremembe toplotnega upora plašča telesa. Lahko vzamemo povprečno vrednost toplotnega upora plašča telesa v coni ugodja 0,0471 m².h.°C/kJ. Toplotni upor plašča telesa med spanjem, ko telo miruje in je presnova na osnovni ravni (bazalni metabolizem), doseže vrednost okrog 0,0729 m².h.°C/kJ. Ker nimamo drugih podatkov, bomo to vrednost vzeli kot spodnjo vrednost, ko temperatura jedra telesa pade na 33 °C. V tem primeru je ΔR_{tl} = 0,0258 m².h.°C/kJ. Če predpostavimo, da je delež plašča telesa 0,40 in je temperatura na površini čela 28 °C, bo srednja temperatura telesa okrog 30 °C.

Čas tolerance bomo računali v intervalu zunanjih temperatur od -20 °C do +20 °C. Ta temperaturni interval bomo razdelili na podintervale po 5 °C. Predpostavili bomo, da je cona ugodja pri zunanji temperaturi 15 °C in izžarevanju toplote 600 kJ/m².h. Pri izračunu dejanskega toplotnega upora bomo upoštevali hitrosti vetra 0, 5, 10, 15 in 20 m/s. Hitrost 15 m/s pomeni 54 km/h. Pri večjih hitrostih je težko delati na prostem.

Izbrali smo zaščitno oblačilo – komplet. Zdaj moramo določiti vrsto in intenziteto aktivnosti, ki naj bo čim bolj realna. Če oseba opravlja delo v okolju, ki je kontaminirano z bojnimi strupi, bo največkrat opravljala delo, zaradi katerega bo izžarevala 600 do 800 kJ/m².h. Lahko računamo le z 600 kJ/m².h, kar je enako izžarevanju toplote med hojo 4 km/h. Če upoštevamo realne razmere, bi bilo to bolj primerno kot bolj intenzivno delo, pri katerem bi se zaščitno oblačilo relativno hitro namočilo z znojem. Opazovano zaščitno oblačilo omogoča cono ugodja pri 15 °C, pri izžarevanju 600 kJ/h toplote skozi površino kože in s tem tudi skozi površino oblačila.

Za ilustracijo problema ugotavljanja časa tolerance bomo operirali s 45 rezultati časa tolerance, ker bomo vzeli devet različnih temperatur okolja in pet hitrosti vetra vključno s stanjem, ko ni vetra. Pri vsakem stanju moramo ugotoviti, ali je toplotni upor našega kompleta premajhen (podhlajanje), optimalen (cona ugodja) ali pa je prevelik (pregrevanje organizma). Temu primerno bomo uporabljali enačbo 12. Pri ohlajanju organizma bomo uporabili ΔR_{tl}. Praviloma bomo upoštevali izgube toplote v procesu dihanja Q_4. Vendar smo prej ocenili, da bomo naredili manj kot 2-odstotno napako, če te izgube v obravnavanem primeru ne upoštevamo. Pri najnižji upoštevani temperaturi -20 °C bi bila napaka nekoliko večja, vendar tega nismo upoštevali v preglednici 4.

Pri pregrevanju organizma pa bomo upoštevali Q_3, ki se nanaša na izgubo toplote zaradi izhlapevanja znoja. Tukaj pa nastane problem. Lahko sicer izračunamo količino znoja, ki mora izhlapeti, da dosežemo ravnovesje med proizvodnjo in oddajo toplote v okolje v danih razmerah. Lahko tudi ugotovimo pogoje, pri katerih bo ta količina znoja zares izhlapela. V tem primeru

does not differ significantly from the temperature of comfort for the observed conditions, incl. clothing (no change of the state of clothing).

However, the change of the body covering thermal resistance cannot be neglected. Its mean value in the zone of comfort is 0.0471 m².h.°C/kJ. During sleep, when a body is resting and metabolism is at its basic level (basal metabolism), the body covering heat resistance achieves the value about 0.0729 m².h.°C/kJ. Since there is no other data available, this value will be taken as a possible bottom value when the body core temperature falls to 33 °C. In that case ΔR_{tl} = 0.0258 m².h.°C/kJ. Supposing that the share of the body covering is 0.4 and that the temperature on the forehead surface is 28 °C, the mean body temperature will be about 30 °C.

The tolerance time will be calculated in the outside temperatures interval from -20 °C to +20 °C. This interval will be divided to subintervals by 5 °C. The zone of comfort will be at the outside temperature 15 °C and at the heat emission 600 kJ/m².h. In the calculation of thermal resistance, the velocities of wind 0, 5, 10, 15 and 20 m/s will be taken into account. The velocity 15 m/s means 54 km/h. At higher velocities, it is difficult to work outdoors.

Protective clothing - a set of clothing has been selected. Now, the type and intensity of activity have to be determined and they shall be as realistic as possible. In an environment, which is contaminated with war poisons, a worker usually performs a work at which he emits from 600 to 800 kJ/m².h. Our calculation can be made only for 600 kJ/m².h, which is the amount emitted by a person walking 4 km/h. In real conditions, walk is more appropriate than intensive work at which protective clothing soaks with sweat relatively quickly. The observed clothing provides the zone of comfort at 15 °C and at heat emission of 600 kJ/h through the skin surface and clothing.

In order to illustrate the problem of defining the tolerance time, 45 results of the time tolerance obtained by combining 9 different environment temperatures and 5 velocities of wind including the non-windy condition will be investigated. For each of these conditions, thermal resistance of the observed clothing will be investigated. It might be too low (cooling down), optimal (zone of comfort) or too high (overheating). Equation 12 will be used accordingly. In the case of body cooling, ΔR_{tl} will be used. As a rule, heat losses during the process of breathing Q_4 will be taken into account, although it has been estimated that the error is less than 2% if such losses are not considered in the investigated case. But et the lowest temperature at -20 °C, error will be few higher. We don't taken it in account in the table 4.

In the process of overheating, Q_3, which refers to the loss of heat as a result of sweating, will be used. Here, a problem appears. It is possible to calculate the amount of sweat, which should evaporate in order to obtain the balance between heat generation and its emission into the environment in the existing conditions. It is also possible to define the conditions in which this amount of sweat will really evaporate. In that case, the tolerance time would be unlimited. But bi bil čas tolerance neskončen. Dejansko pa moramo upoštevati najbolj verjetno stanje okolja in organizma in pod temi pogoji izračunati maksimalno količino izhlapelega znoja, ki je v večini primerov manjša od optimuma. Kljub temu izredno podaljša čas tolerance oziroma čas, v katerem dosežemo kritično stanje organizma (39 °C in 180 utripov srca/minuto).

Toploto Q_1, ki jo oseba proizvede v telesu in ki ne zajema toplote za delovanje mišic, notranjih organov in segrevanje izdihanega zraka, smo vzeli 600 kJ/m^2.h. Ta je sicer lahko večja ali manjša, odvisno od vrste in intenzitete dela osebe v kontaminiranem okolju. To je obenem toplota, ki jo mora oseba oddati skozi površino kože in potem skozi površino oblačila v okolje. Če je ta izguba toplote enaka proizvodnji, je $\Delta Q_b = 0$, je oseba v coni ugodja. Predpostavimo, da ugotavljamo čas tolerance pri temperaturi okolja 20 °C do –20 °C in hitrosti vetra 0 do 20 m/s. Lahko pričakujemo, da komplet zaščitnega oblačila nima vrednosti toplotnega upora, ki bi zadostovala za temperaturo okolja –20 °C niti tedaj, ko okolje ni vetrovno oziroma v = 0 m/s. Obenem predpostavimo, da je bil prej organizem osebe, ki gre v okolje, ki ima temperaturo –20 °C, v coni ugodja. To pomeni, da je vrednost ΔRti v začetku procesa manjša kot v času, ko se povprečna temperatura telesa zniža s 36,6 °C na 30 °C. Kot smo že prej omenili, ima ΔR_{ti} vrednost 0,0258 m^2.h.°C/kJ. Če se toplotni upor plašča telesa linearno povečuje z zniževanjem srednje temperature telesa, potem bi lahko računali s polovično vrednostjo povečanja oziroma z 0,0129 m^2.h.°C/kJ. To je srednja vrednost spremembe toplotnega upora plašča telesa.

Če je povprečna temperatura telesa 30 °C, povprečna temperatura ugodja 36,6 °C, specifična toplota 3,5 kJ/kg.°C in masa uporabnika oblačila 70 kg, izračunamo z enačbo 6, da je ΔQ_b = 1.617 kJ. To je maksimalna količina toplote, ki jo lahko izčrpamo iz telesa, da se ohladi s 36,6 na 30 °C. To je le en parameter v enačbi 12, kjer se R_{s1} nanaša na skupni toplotni upor, ki je potreben, da oseba ostane v coni ugodja ne glede na dejanske razmere. R_{s1} je enak realnemu toplotnemu uporu R_{s2} takrat, ko ta pomeni cono ugodja in je $\Delta Q_b = 0$. Za to stanje enačba 12 ne velja, ker je rezultat 0/0; oziroma bi dobili neskončno število rešitev. Kljub temu ima določen smisel, če to vzamemo kot stanje v coni ugodja, ki nima časovne omejitve.

Za izračun toplotnega upora R_{s2} uporabimo enačbe od 1 do 3. V preglednicah 1 in 2 so podane vrednosti parametrov kakovosti tkanin, ki so potrebni za izračun toplotnega upora zaščitnega oblačila. Skupni toplotni upor R_s kompleta v mirnem vremenu je 0,012068 m^2.h.°C/kJ. Debelina kompleta je 0,00163 m in koeficient toplotne prevodnosti λ = 0,135068 kJ/m.h.°C. Toplotni upor plasti mirnega zraka R_a na površini oblačila je 0,017875 m^2.h.°C/kJ. Skupni toplotni upor kompleta, R_{s2} = 0,029943 m^2.h.°C/kJ.

in fact, the most probable condition of the environment and of the organism shall be considered and on that basis, the maximum amount of evaporated sweat calculated. Although in most cases this amount is lower than the optimal amount, it considerably extends the tolerance time, i.e. the time in which critical condition of an organism is achieved (39 °C and 180 heartbeats per minute).

Heat Q_1, which is generated in the body and which does not encompass the heat required for muscles and internal organs functioning as well as for the exhaled air heating, is considered 600 kJ/m^2.h. It can be higher or lower, depending on the type and intensity of work in the contaminated environment. This is also the heat, which should be emitted through the skin surface and then through the surface of clothing. If this loss of heat is the same as its generation then ΔQ_b = 0. A person is the comfort zone. Let us suppose that the tolerance time at the temperature of environment from 20 °C to -20 °C and at the velocity of wind from 0 to 20 m/s is going to be determined. It can be expected that the set of protective clothing does not provide such thermal resistance, which would suffice for the temperature of environment -20 °C either in the case of still, non-windy weather when v = 0 m/s. It is also supposed that prior to entering the environment having the temperature -20 °C, the observed person was in the zone of comfort. That means that at the beginning of the process the value of ΔR_{ti} is lower than in the time when the mean body temperature falls from 36.6 °C to 30 °C. As already mentioned, the value of ΔR_{ti} is 0.0258 m^2.h. °C/kJ. If thermal resistance of the body covering increases linearly with the decrease of the mean body temperature, the half value of the increase, i.e. 0.0129 m^2.h. °C/kJ, can be used in calculations. This is the mean value of the body covering thermal resistance change.

If the mean body temperature is 30 °C, the mean body temperature of comfort 36.6 °C, the specific heat 3.5 kJ/kg. °C and the clothing user's mass 70 kg, it can be calculated by using Equation 6 that ΔQ_b = 1.617 kJ. This is the maximum amount of heat, which can be extracted from the body in order to cool the mean body from 36.6 to 30 °C. This is only one of the parameters in Equation 12 in which R_{s1} refers to total thermal resistance, which is required by the person to stay in the zone of comfort regardless of actual conditions. R_{s1} is equal to the real thermal resistance R_{s2} when the latter means the zone of comfort.

Equations 1 to 3 are used for calculating thermal resistance R_{s2}. Tables 1 and 2 present the values of the quality parameters of fabric, which are required for calculating thermal resistance of protective clothing. Total thermal resistance R_s of the set of clothing in still weather is 0.012068 m^2.h. °C/kJ. The thickness of the set of clothing in still weather is 0.00163 m and heat conductivity coefficient λ = 0.135068 kJ/m.h. °C. Thermal resistance of the motionless air layer R_a on the surface of clothing is 0.017875 m^2.h. °C/kJ. Total thermal resistance of the set of clothing is R_{s2} = 0.029943 m^2.h. °C/kJ.

Next step is determination of the temperature of environment in still weather when the set of clothing provides the

Naslednji korak je ugotavljanje temperature okolja v mirnem vremenu, ko komplet omogoča doseganje temperature ugodja (T_{skc} = 33 °C). Za ta namen uporabimo enačbo 15:

temperature of comfort (T_{skc} = 33 °C). For this purpose, Equation 15 is used.

With Equation 15 thermal resistance required for the body to

$$R_{s1} = \frac{(T_{skc} - T_{en})}{Q_2} \qquad (15)$$

Z enačbo 15 ugotovimo potrebni toplotni upor pri dani količini izžarjene toplote Q_2 in temperaturi okolja T_{en}, da telo ostane v coni ugodja. Če je toplotni upor R_{s1} večji od dejanskega R_{s2}, se bo ohlajalo telo opazovane osebe. Če sta oba toplotna upora izenačena, je oseba v coni ugodja. Če pa je $R_{s1} < R_{s2}$, se bo kopičila toplota v telesu opazovane osebe in se ji bo zvišala tudi temperatura. Ker pa se povprečna temperatura telesa ne sme zvišati nad kritično temperaturo 39 °C, morajo biti izpolnjeni pogoji, ki omogočajo pretok izhlapelega znoja v okolje. V tem primeru lahko z enačbo 16 ugotovimo količino znoja, ki mora izhlapeti v enoti časa, da se temperatura na površini prsi ne poveča na primer nad 35 °C. Pri tej temperaturi je skoraj vsa površina telesa prekrita z znojem.

stay in the comfort zone at the given amount of emitted heat Q_2 and temperature of environment T_{en} can be calculated. If thermal resistance R_{s1} is higher than R_{s2}, the body of the observed person will cool down. If the two thermal resistances are equal, the observed person is in the zone of comfort. If R_{s1} is lower than R_{s2}, heat will accumulate in the body of the observed person and the body temperature will increase. Since the mean body temperature may not rise above the critical temperature 39 °C, the conditions which allow the flow of the evaporated sweat into the environment should be satisfied. By using Equation 16, it is possible to determine the amount of sweat, which has to evaporate in a unit time in order to prevent the increase of the temperature on chest above for example 35 °C. At this temperature, almost the entire body surface is covered with sweat.

$$R_{s2} = \frac{T_{sk*} - T_{en}}{Q_{2*}}; \quad Q_{2*} = Q_1 - Q_3; \quad T_{en} = T_{sk*} - R_{s2}Q_{2*} \qquad (16)$$

kjer so: R_{s2} – realni toplotni upor suhega oblačila, Q_{2*} – del proizvedene toplote Q_1, ki se izžari skozi površino oblačila v okolje, Q_3 – del proizvedene toplote, ki se porabi za izhlapevanje znoja, T_{sk*} – temperatura na površini prsi, pri kateri je skoraj celotna površina telesa prekrita z znojem. V našem primeru je to temperatura 35 °C.

V našem primeru ima toplota Q_1 vrednost 600 kJ/m^2. Vsa ta toplota mora biti oddana skozi površino kože in površino oblačila v okolje. Če je vrednost toplotnega upora realnega oblačila v danih razmerah previsoka, se bo toplota kopičila v telesu opazovane osebe. V našem primeru ima R_{s2} v mirnem vremenu vrednost 0,02994 m^2.h.°C/kJ. Če je na primer temperatura okolja T_{en} = 30 °C, je T_{sk*} = 35 °C. Vprašanje je, koliko toplote bo oddane v okolje skozi oblačilo. Odgovor je 167 kJ/h. To je vrednost Q_{2*}. Vsa preostala toplota se mora porabiti za izhlapevanje znoja, da se ne bi začela kopičiti v telesu, kar bi povzročilo dvig povprečne temperature telesa. Toplota Q_3, ki je na voljo za izhlapevanje znoja, ima vrednost 433 kJ/h.

Specifična toplota telesa je okrog 3,5 kJ/kg.°C. Toplota izhlapevanja vode je 2.260 kJ/kg. Voda vre pri 100 °C. Če je povprečna temperatura telesa 37 °C, potrebujemo 4,4 kJ za segrevanje 1 grama vode (znoja) na 100 °C. Za izhlapevanje tega grama znoja potrebujemo 2,26 kJ. Skupaj potrebujemo 6,66 kJ toplote za izhlapevanje enega grama znoja. Da porabimo 433 kJ/h, mora izhlapeti 65 gramov znoja v eni uri. Če so pogoji

where R_{s2} is real thermal resistance of dry clothing, Q_{2*} is a fraction of generated heat Q_1, which is emitted through the surface of clothing into the environment, Q_3 is a fraction of generated heat, which is used for sweat evaporation, T_{sk*} is the temperature on the chest surface at which the almost entire body surface is covered with sweat. In our case, this is the temperature 35 °C.

In our case, heat Q_1 has the value 600 kJ/m^2. This amount has to be emitted through the surface of the skin and clothing into the environment. If the value of thermal resistance of real clothing is too high in given conditions, heat will accumulate in the observed person's body. In the investigated case, R_{s2} has the value 0.02994 m^2.h.°C/kJ in still weather. If for example the environment temperature T_{en} is 30 °C, T_{sk*} is 35 °C. The question is which amount of heat will flow through clothing into the environment. The answer is 167 kJ/h. This is the value Q_{2*}. The rest of the heat should be used for sweat evaporation in order not to accumulate in the body, which would result in the increase of the mean body temperature. Heat Q_3 which is available for sweat evaporation has the value 433 kJ/h.

Specific body heat is about 3.5 kJ/kg °C. Water vapor heat is 2,260 kJ/kg. Water starts to boil at 100 °C. If the mean body temperature is 37 °C, 4.4 KJ are required for heating 1 gram of water (sweat) to 100 °C. 2.26 kJ are required for evaporation of this 1 gram of sweat. In total, 6.66 kJ of heat are required for evaporation of 1 gram of sweat. In order to consume 433 kJ/h, 65 grams of sweat should evaporate in 1 hour. If the conditions for such rapidity of evaporation are fulfilled, the za takšno hitrost izhlapevanja izpolnjeni, bo ostala nespremenjena temperatura na površini prsi. Ker je pod temi pogoji hitrost izločanja znoja precej večja, ne bo primanjkovalo znoja za izhlapevanje. Zunanja površina oblačila je okrog 2 m^2. To pomeni, da morajo biti izpolnjeni pogoji za izhlapevanje 32,5 g/m^2.h. Realni pretok toplote skozi oblačilo bo verjetno večji od 300 kJ/h. To pomeni, da v realnih razmerah (zmočena vsaj spodnja plast oblačila) ne bo potrebe po večji hitrosti izhlapevanja znoja kot okrog 20 g/h.

Časa tolerance ni tako lahko ugotoviti, ker ne poznamo vseh potrebnih parametrov. Vendar je mogoče dovolj natančno ugotoviti ta čas vsaj v mejah odstopanja, ki so približno tudi meje razlik med posameznimi osebami.

Naš komplet zaščitnega oblačila omogoča doseganje ravnovesja med toplotama Q_1 in Q_2 pri temperaturi okolja T_{en} = 15 °C. Pri temperaturi okolja 15 °C sta R_{s1} in R_{s2} izenačena – imata enako vrednost. V teh razmerah enačba 12 ni definirana, saj je rezultat 0/0. Kljub matematičnemu formalizmu glede na realno fizikalno stanje je to stanje v času ugodja. Z drugimi besedami – subjekt bi v teh razmerah ostal v coni ugodja neomejeno dolgo. To seveda velja, če se ne spremeni vrednost nobenega parametra, ki vpliva na skupni toplotni upor. Toplotni upor oblačila v določenih razmerah pri ohlajanju računamo s pomočjo enačbe 1 s tem, da koeficient toplotne prevodnosti računamo s pomočjo enačbe 4. Ker upoštevamo le suho oblačilo, bo $\Delta G = 0$. Obenem ne bomo upoštevali vpliva spremembe temperature okolja na R_{s2}. Pri podhlajenosti telesa moramo upoštevati spremembo toplotnega upora plašča telesa ΔR_{ti}. Ta toplotni upor prištejemo skupnemu toplotnemu uporu R_{s2}. Temperatura na površini čela T_{sk} je pri kritični temperaturi podhladitve 28 °C. V tem primeru je $\lambda_0 = \lambda$. Realni skupni toplotni upor oblačila R_{s2} računamo z enačbo 5. Koeficient toplotne prevodnosti λ, kot tudi debelino oblačila izračunamo, z enačbo 1.

Predpostavili bomo, da se vrednost koeficienta toplotne prevodnosti ne spreminja ne glede na spremembo temperature okolja in hitrosti vetra. Pri vsakokratni spremembi temperature okolja (temperatura na površini kože se ne spreminja – je 33 °C), debelino oblačila prilagodimo novem stanju, tako da R_{s1} (primerjalni toplotni upor) v novih razmerah zadostuje za ustvarjanje cone ugodja. Debelino oblačila izračunamo z enačbo 17. Enačba 17 se nanaša na stanje brez vetra. Če je vetrovno, začetni vrednosti koeficienta toplotne prevodnosti λ prištejemo vrednost, ki je posledica vpliva vetra. Primerjalni toplotni upor R_{s1} se nanaša na toplotni upor, ki je potreben, da se obdrži cona ugodja ne glede na spremembo temperature okolja in spremembo hitrosti vetra. Za primer vzemimo temperaturo okolja –10 °C pri hitrosti vetra 1 m/s, kar pomeni stanje okolja brez vetra. Za ugotavljanje potrebnega toplotnega upora

temperature on the chest surface will remain unchanged. Since the rapidity of sweat evaporation is much higher at such conditions, there will be enough sweat for evaporation. The outer surface of clothing is about 2 m^2. This means that the conditions, which will enable evaporation of 32.5 grams of sweat per 1 m^2 in 1 hour, should be provided. However, real flow of heat through clothing will be probably higher than 300 kJ/h. This means that in real situation (bottom clothing layer at least to be wetted), there will be no need for higher speed of sweat evaporation than about 20 g/h.

It is not easy to determine the tolerance time as all required parameters are not known. However, it is possible to determine it quite precisely at least within the limits of a deviation, which would correspond to the limits of differences between individual persons.

With the selected set of clothing the balance between heats Q_1 and Q_2 at environment temperature T_{en} = 15 °C can be achieved. At the environment temperature 15 °C, R_{s1} and R_{s2} are equal – they have the same value. According to Equation 12, this is the zone of comfort. Despite mathematical formalism it is in view of real physical state the comfort zone. In other words, in such conditions the observed person would stay in the zone of comfort for an unlimited period of time. Of course, this applies only if the value of any parameter, which has effect on total thermal resistance, remains unchanged. Thermal resistance of clothing in certain conditions during the process of cooling is calculated by using Equation 1; the heat conductivity coefficient is calculated by using Equation 4. Since only dry clothing is considered, $\Delta G = 0$. The effect of the change of the environment temperature to R_{s2} will not be taken into account. In the case of body cooling, the change of thermal resistance of the body covering ΔR_{ti} should be considered. This thermal resistance should be added to total thermal resistance R_{s2}. The temperature on the forehead surface T_{sk} is 28 °C at the critical temperature of cooling down. In that case $\lambda_0 = \lambda$. Total real thermal resistance of clothing R_{s2} is calculated by using Equation 5. Heat conductivity coefficient λ and the thickness of clothing are calculated by using Equation 1.

Suppose that the value of the heat conductivity coefficient does not change with the change of the environment temperature and the velocity of wind. At each change of the environment temperature (the temperature on the skin surface does not change – it is 33 °C), the thickness of clothing is adjusted to the new situation so that in new conditions R_{s1} (comparative thermal resistance) is sufficient to create the zone of comfort. The thickness of clothing is calculated with Equation 17. Equation 17 applies to non-windy conditions. In windy conditions, the value resulting from the influence of wind should be added to the initial value of heat conductivity coefficient λ. Comparative thermal resistance R_{s1} refers to thermal resistance, which is required to preserve the zone of comfort regardless of the change of the environment temperature and the velocity of wind. Suppose that the environment temperature is –10 °C and the velocity of wind 1 m/s, which means the non-windy conditions. To determine the required oblačila za cono ugodja uporabimo enačbo 15. Izračunana vrednost je 0,071667 m².h.°C/kJ. Če želimo ugotoviti R_{s1} pri katerikoli hitrosti vetra, moramo najprej izračunati toplotni upor primerjalnega oblačila v mirnem vremenu, da ugotovimo debelino oblačila. Debelino oblačila potrebujemo, da izračunamo skupni toplotni upor oblačila pri določeni hitrosti vetra. V mirnem vremenu debelino oblačila pri določeni temperaturi okolja (temperatura T_{skc} je 33 °C) izračunamo z naslednjo splošno enačbo:

thermal resistance of clothing for the zone of comfort, Equation 15 is used. The calculated value is 0.071667 m².h.°C/kJ. To determine R_{s1} at any velocity of wind, thermal resistance of clothing in still weather shall be calculated first in order to be able to determine the thickness of clothing. The thickness of clothing is required to calculate total thermal resistance of clothing at certain velocity of wind. In still weather, the thickness of clothing at certain environment temperature (temperature T_{skc} is 33 °C) is calculated by using the following universal equation:

$$d=\left(R_{s1(T,v)}-R_a\right)\lambda \qquad (17)$$

V našem primeru
(T_{en} = −10 °C;
T_{skc} = 33 °C; λ = 0,135068 kJ/m.h.°C;
$R_{s1(T,v)} = R_{s1(-10,0)}$ = 0,071667 m².h.°C/kJ;
R_a = 0,017875 m².h.°C/kJ), parametri poroznosti oblačila niso spremenjeni. Za ta primer je potrebna debelina oblačila 0,007266 m. Pri hitrosti vetra 10 m/s se vrednost tega toplotnega upora zmanjša in znaša 0,013117 m².h.°C/kJ. To pomeni, da je $R_{s1(-10,10)}$ = 0,013117 m².h.°C/kJ. Ta toplotni upor ne zadostuje za doseganje cone ugodja. Zato moramo povečati skupni toplotni upor $R_{s1(-10,10)}$ na skupni toplotni upor $R^*_{s1(-10,10)}$, ki bo omogočil cono ugodja pri temperaturi −10 °C in hitrosti vetra 10 m/s. Potrebni skupni toplotni upor $R^*_{s1(-10,10)}$ v teh razmerah, lahko izračunamo z naslednjo enačbo:

In our case
(T_{en} = −10 °C;
T_{skc} = 33 °C; λ = 0,135068 kJ/m.h.°C;
$R_{s1(T,v)} = R_{s1(-10,0)}$ = 0,071667 m².h.°C/kJ;
R_a = 0,017875 m².h.°C/kJ), porosity parameters are not changed. The required thickness of clothing is 0.007266 m. At the velocity of wind 10 m/s, the value of this thermal resistance decreases to 0.013117 m².h.°C/kJ. This means that $R_{s1(-10,10)}$ = 0,013117 m².h.°C/kJ. Such thermal resistance is not high enough to provide the zone of comfort. That is why summary thermal resistance $R_{s1(-10,10)}$ should be increased to $R^*_{s1(-10,10)}$ is summary thermal resistance, which is required to create the zone of comfort at the environment temperature −10 °C and the velocity of wind 10 m/s. The required summary thermal resistance $R^*_{s1(-10,10)}$ in such conditions can be calculated by using the following equation:

$$R^*_{s1(-10,10)}=R_{s1(-10,0)}+\Delta R_{s1[(-10,0)-(-10,10)]}=2R_{s1(-10,0)}-R_{s1(-10,10)} \qquad (18)$$

kjer so: $R^*_{s1(-10,10)}$ – potrebni skupni toplotni upor oblačila pri okoljski temperaturi −10 °C in hitrosti vetra 10 m/s, $R_{s1(-10,0)}$ – potrebni skupni upor oblačila za cono ugodja pri temperaturi −10 v mirnem vremenu, $\Delta R_{s1[(-10,0)-(-10,10)]}$ – zmanjšanje vrednosti skupnega toplotnega upora (temperatura okolja −10 °C) pri hitrosti vetra 10 m/s v primerjavi s toplotnim uporom oblačila v mirnem vremenu (zaradi vpliva vetra), $R_{s1(-10,10)}$ – skupni upor opazovanega oblačila pri temperaturi okolja −10 °C in hitrosti vetra 10 m/s. Z enačbo 18 izračunamo potrebni toplotni upor, da oseba ostane v coni ugodja pri katerikoli hitrosti vetra pri dani temperaturi okolja. Pri uporabi enačbe 17 upoštevamo koeficient toplotne prevodnosti realnega oblačila, R_a v mirnem vremenu brez vetra in vrednost $R_{s1(T,v)}$, ki smo jo izračunali s pomočjo enačbe 15.

Potrebni skupni toplotni upor $R^*_{s1(-10,10)}$ = 2*0,071667 – 0,013117 = 0,130217 m².h.°C/kJ. Vrednost potrebnega toplotnega upora pri hitrosti vetra 10 m/s se izredno poveča.

Ko smo izračunali vse vrednosti uporov R_{s1} in R_{s2} pri vseh temperaturah okolja in vseh hitrostih vetra, s pomočjo enačbe 12 izračunamo čase tolerance. Pod temi pogoji (T = −10 °C, v = 10 m/s) je realna vrednost skupnega

where $R^*_{s1(-10,10)}$ – required summary thermal resistance of clothing at environment temperature −10 °C and velocity of wind 10 m/s, $R_{s1(-10,0)}$ – required summary thermal resistance of clothing for the zone of comfort at temperature −10 in still weather, $\Delta R_{s1[(-10,0)-(-10,10)]}$ – decrease of summary thermal resistance value (environment temperature −10 °C) at velocity of wind 10 m/s compared with summary thermal resistance of clothing in still weather (due to influence of wind), $R_{s1(-10,10)}$ – summary thermal resistance of investigated clothing at environment temperature −10 °C and velocity of wind 10 m/s. By using Equation 18, thermal resistance required to preserve the zone of comfort at any velocity of wind at a given environment temperature can be calculated. In Equation 17, heat conductivity coefficient of real clothing R_a in still, non-windy weather and $R_{s1(T,v)}$ calculated by using Equation 15 are taken into account.

The required summary thermal resistance is $R^*_{s1(-10,10)}$ = 2*0,071667 – 0,013117 = 0,130217 m².h.°C/kJ. The value of the required thermal resistance remarkably increases at the velocity of wind 10 m/s.

When the values of R_{s1} and R_{s2} at all environment temperatures and all velocities of wind are calculated, the tolerance times can be calculated by using Equation 12. Under these conditions (T = −10 °C, v = 10 m/s), the real value of summary toplotnega upora oblačila R_{s2} = 0,010846 m^2.h.°C/kJ. V mirnem vremenu je 0,029943 m^2.h.°C/kJ oziroma se zmanjša na 36 % prvotne vrednosti. Na to razliko precej vpliva izredna sprememba toplotnega upora plasti mirnega zraka R_a na površini oblačila. V teh razmerah se človekovo telo ohlaja. Zato moramo dodati polovico povečane vrednosti toplotnega upora plašča telesa ΔR_{ti}. Ta ima vrednost 0,0129 m^2.h.°C/kJ. V tem primeru bo čas tolerance le 1,41 ur ali 85 minut. K tako kratkemu času tolerance precej pripomore poroznost oblačila. Ta je pri hitrosti vetra 10 m/s zelo velika in znaša 112 m^3/m^2.h.

4.7 Pregrevanje organizma

Pregrevanje organizma nastane takrat, ko se začne kopičiti toplota v organizmu, oziroma takrat, ko sta hitrosti proizvodnje toplote in zunanje – dodatne toplotne obremenitve večje, kot je hitrost oddajanja toplote v okolje. Posledica tega stanja je zviševanje povprečne temperature organizma. V pregretem stanju organizma se spremeni koeficient toplotne prevodnosti plašča telesa. Zaradi pospešenega kroženja krvi postane plašč celo slabši termoizolator kot voda. Na ravni kritične temperature telesa – okrog 39 °C in še prej, pri povprečni temperaturi telesa 37 °C, se izenačita temperatura plašča in temperatura jedra telesa in smemo predpostaviti, da je temperatura notranjosti enaka povprečni temperaturi telesa. Temperatura okolja je lahko celo višja, enaka ali nižja kot temperatura na površini kože.

V primerih, ko se telo pregreva – kopičenje toplote v telesu, je ΔQ_b pozitiven. Pri računanju časa tolerance ne upoštevamo ΔR_{ti}, ker pač več ne obstoji toplotni upor plašča telesa, saj prevaja toploto bolje kot voda, ker v koži in podkožnem tkivu hitro kroži kri in prinaša toploto iz notranjosti telesa v smeri njegove površine.

Pri pregrevanju telesa subjekta je $Q_1 > Q_2$ – toplota se kopiči v telesu in se zdi, da bi dobili negativno vrednost časa tolerance, kar je fizikalni nesmisel oziroma čas tolerance bi bil le čas, potreben za zvišanje telesne temperature s 36,6 na 39 °C. Če analiziramo enačbo 12, bomo ugotovili, da je potrebna količina oblačila negativna oziroma, da bi se lahko pregrevali tudi, če bi bili popolnoma nagi. Dejansko dobimo pozitivno vrednost časa tolerance, ki ga izračunamo z enačbo 12. Izhlapevanje znoja omogoča podaljšanje časa tolerance pri pregrevanju organizma. Če ni omogočeno izhlapevanje znoja, je čas tolerance lahko zelo kratek, če je upor prehodu vodne pare skozi oblačilo neskončen. To je primer uporabe kaširanega ali gumiranega oblačila, ki ni prepustno ne za zrak ne za vodno paro. Ker je komplet zaščitnega oblačila zelo porozen, bodo hlapi znoja preneseni v okolje. Hitrost pretoka vodne pare (deleža izhlapelega znoja) bo odvisna

thermal resistance of clothing is R_{s2} = 0,010846 m^2.h.°C/kJ. In still weather, it is 0.029943 m^2.h.°C/kJ, which means that it decreases to 36% of its initial value. The substantial change of the still air layer thermal resistance R_a on the clothing surface highly influences this difference. In such conditions, a human body starts to cool down. That is why half of the increased value of the body covering thermal resistance ΔR_{ti} shall be added. It has the value 0.0129 m^2.h.°C/kJ. In that case, the tolerance time will be only 1.41 hours or 85 minutes. The porosity of clothing considerably contributes to such short tolerance time. At the velocity of wind 10 m/s, it is very high, i.e. 112 m^{3}m^{-2}.h^{-1}.

4.7 Overheating of Body

Overheating of a body occurs when the heat starts to accumulate in the organism or, in other words, when the rapidity of the heat generation and external – additional thermal loading is higher than the rapidity of heat emission into the environment. The result is the increase of the mean body temperature. In the overheated state, the heat conductivity coefficient of the body covering undergoes change. Due to the accelerated blood circulation, the body covering becomes even worse thermal insulator than water. At the level of the body critical temperature, which is about 39 °C, or even already at the mean body temperature, which is 37 °C, the temperature of the body covering and that of the body core become equal and it may be supposed that the internal body temperature is the same as the mean body temperature. The environment temperature can be higher, the same or lower than the temperature on the skin surface.

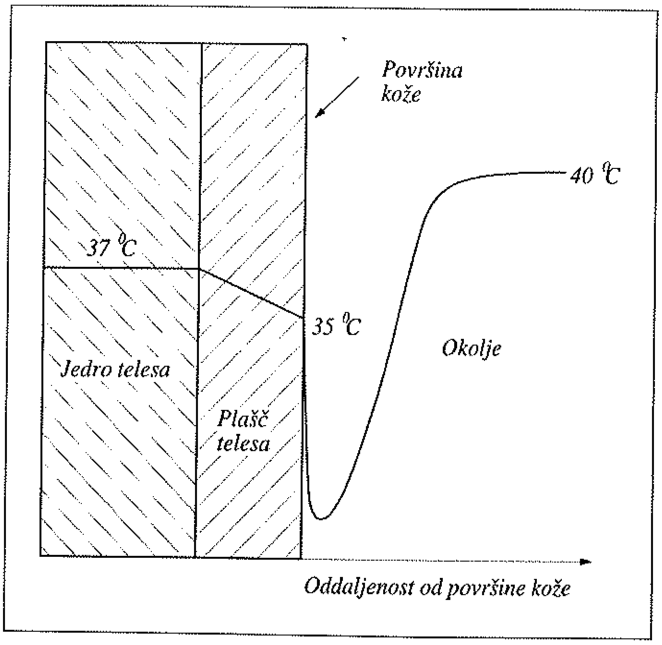
In the case of body overheating (accumulation of heat in the body), ΔQ_b is positive. In the calculation of the tolerance time, ΔR_{ti} is not considered because thermal resistance of the body covering does not exist any more. Namely, the body covering practically conduct water better than water due to quick blood circulation in the skin and subcutaneous tissue, which transfers heat from the body inside towards its outside.

In the conditions of body overheating, $Q_1 > Q_2$ – the heat accumulates in the body and it seems that a negative value of the tolerance time would be obtained, which is a physical nonsense because the tolerance time would be only the time required to increase the body temperature from 36.6 to 39 °C. The analysis of Equation 12 shows that the required amount of clothing is negative, which also means that overheating will occur even with a completely naked body. In fact, a positive value of the tolerance time is obtained, which is calculated by using Equation 12. Sweat evaporation enables prolongation of the tolerance time in the conditions of body overheating. If sweat evaporation is not provided, the tolerance time can be very short in the case of the resistance to water vapors transmission through clothing being infinite. This is the case with rubber coated or rubberized clothing, which is impermeable for water and water vapors. Since the set of protective clothing is very porous, sweat vapors will be transported into the environment.

od relativne vlage v okolju, temperature okolja in hitrosti vetra. To pomeni, da bomo upoštevali toploto Q_3, ki je potrebna za izhlapevanje znoja.

V enačbi 16 je temperatura T_{sk*} temperatura na površini prsi oziroma čela, ki je dovolj visoka, da se tako rekoč vsa površina telesa – koža prekrije z znojem. Ta temperatura je 35 °C. Pri tej temperaturi je osebi zelo toplo. Kljub temu lahko opravlja določeno aktivnost v kontaminiranem okolju. Do 90 % površine kože je prekrito z znojem (preglednica 3). Delež plašča telesa se je zmanjšal. Verjetno ni večji od 0,1 oziroma 10 % celotne mase osebe.

V tem primeru bi bila povprečna temperatura telesa 36,8 °C, kar je skoraj izenačena temperatura plašča in temperatura jedra telesa. Toda znoj izhlapeva s površine kože. Posledica tega je hlajenje površine kože. Lokalna temperatura na površini kože je nižja od povprečne temperature telesa. Ta razlika omogoče pretok toplote proti površini telesa. Celo tedaj, ko je temperatura okolja višja od temperature na površini kože, je temperatura zraka neposredno na površini kože nižja od povprečne temperature telesa in temperature okolja. Zato je mogoč pretok toplote s površine kože, ki ima nižjo temperaturo kot okolje na določeni razdalji od površine kože. Za izhlapevanje določene enote mase znoja (vode) potrebujemo določeno količino toplote. To toploto dobimo iz telesa (telo se hladi) in zraka na neposredni površini kože oziroma na površini oblačila. Zato se ta zrak ohladi na nižjo temperaturo, kot je povprečna temperatura telesa, kar omogoča pretok toplote iz pregretega telesa v še bolj vroče okolje. Ta proces je ilustriran na sliki 3.



Slika 3: Mehanizem pretoka toplote s površine kože v vroče okolje

The rapidity of the water vapors flux (the fraction of the evaporated sweat) will depend on the relative humidity of environment, temperature of environment and velocity of wind. This means that heat Q_3, which is required for sweat evaporation, will be considered.

In Equation 16, temperature T_{sk*} is the temperature on the chest surface or forehead surface , which is high enough to cover practically the entire body superficies – skin with sweat. This temperature is 35 °C. At this temperature a person is very warm. Nevertheless, a person can perform certain activity in a contaminated environment. Up to 90% of the skin surface is covered with sweat (Table 3). The share of the body covering has diminished and is probably not higher than 0.1 or 10% of the total person's mass.

In that case, the mean body temperature would be 36.8 °C, which means that the temperature of the body covering and the temperature of the body core are almost equal. However, sweat evaporates from the skin surface. The result is cooling of the skin surface. Local temperature on the skin surface is lower than the mean body temperature. This difference enables the heat flow towards the body superficies. Even in the case when the temperature of environment is higher than the temperature on the skin surface, the temperature of the air close to the skin surface is lower than the mean body temperature and the environment temperature. That is why the heat can flow from the skin surface, which has lower temperature than the environment at a certain distance from the skin surface. For evaporation of a certain mass unit of sweat (water), a certain amount of heat is required. This heat is obtained from the body (the body is cooling down) and the air close to the skin or clothing surface. As a result, the air cools down to the temperature lower than the mean body temperature, which enables the flow of the heat from the overheated body into still hotter environment. This process is illustrated in Figure 3.

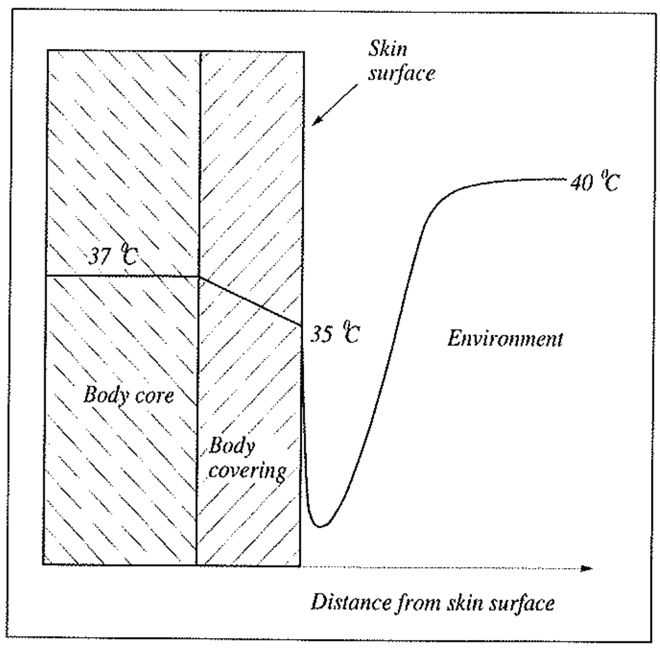


Figure 3: Mechanism of heat flow from skin surface into hot environment

Ko smo izračunali vse vrednosti R_{s1} in R_{s2} pri vseh temperaturah in hitrostih vetra, izračunamo čase tolerance za vsa ta stanja. Tedaj ko se organizem pregreva, bomo predpostavili, da so izpolnjeni pogoji, da se odvečna toplota sprosti v okolje s pomočjo izhlapevanja znoja. Osebi je precej vroče, vendar je vsaj še 60 minut sposobna opravljati potrebne aktivnosti.

V preglednici 4 so izračunani časi tolerance, ki veljajo za ohlajevanje organizma. Če ni vetra, se doseže ravnovesje med proizvodnjo in izžarevanjem toplote pri temperaturi okolja in proizvodnji toplote 600 kJ/m^2.h pri 15 °C. Vrednosti 14,13 in 2,16 ure pri temperaturi okolja 5 oziroma 10 °C v mirnem vremenu in 27,14 ure pri temperaturi okolja 20 °C in hitrosti vetra 5 m/s, ki so prikazani v preglednici 4, niso časi tolerance, ker smo jih dosegli pri višjih temperaturah, kot je kritična temperature, za katero računamo čas tolerance. Ko smo enkrat dosegli srednje vrednosti temperature telesa 33,35 oziroma 32 °C, se v teh razmerah nič več ne znižuje srednja temperatura telesa in smo lahko v tem okolju neomejen čas. Zato te vrednosti ne sodijo v časovno toleranco, kot je ta definirana v tem delu.

After calculating the values of R_{s1} and R_{s2} at all temperatures and velocities of wind, the tolerance times for all these states are calculated. In the cases of the organism overheating, it will be supposed that the conditions for liberating surplus heat into the environment by means of sweat are fulfilled. A person is rather hot but it is capable of performing necessary activities for 60 minutes at least.

In Table 4, the tolerance times, which apply to the conditions of the body cooling down, are calculated. When there is no wind, the balance between heat generation and heat emission is obtained at the environment temperature at 15 °C and heat generation 600 kJ/m^2.h. The values 14.13 and 2.16 hours at the environment temperature 5 or 10 °C in still weather and 27.14 hours at the environment temperature 20 °C and at the velocity of wind 5 m/s, which are presented in Table 4, are not the tolerance times because they have been obtained at temperatures higher than the critical temperature for which the tolerance time is calculated. When the body temperature mean values 33, 35 or 32 °C are obtained, the mean body temperature stops to fall and a person can stay in such conditions for unlimited period of time. That is why these values cannot belong to the tolerance time as is defined in this part.

Preglednica 4: *Čas tolerance, ki je izračunan z enačbo 12, v urah za komplet zaščitnega oblačila glede na temperaturo okolja in hitrost vetra pri proizvodnji toplote Q_1 osebe, ki znaša 600 kJ/h*

Table 4: Tolerance time in hours, which is calculated with Equation 12, for the set of protective clothing in dependence of environment temperature and velocity of wind at heat generation Q_1 600 kJ/h

Temperatura / **Temperature °C**	***Hitrost vetra, m/s /* Velocity of wind, m/s**				
	0	**5**	**10**	**15**	**20**
	***Čas tolerance glede na temperaturo in hitrost vetra, ur /* Tolerance time in dependence of temperature and velocity of wind in hours**				
–20	3,45	1,66	1,05	0,87	0,79
–15	4,45	1,95	1,21	0,99	0,90
–10	6,26	2,37	1,41	1,14	1,04
–5	10,57	3,02	1,69	1,36	1,23
0	25,33	4,16	2,13	1,68	1,50
5	14,13[1]	6,66	2,87	2,20	1,96
10	2,16[2]	16,21	4,43	3,20	2,80
15	***	44,12	9,87	5,93	4,91
20		27,14[3]	95,31	44,15	21,27

[1] V tem času se temperatura na površini telesa zniža s 33 °C na 30 °C in srednja temperatura telesa s 36,6 na 33 °C; ΔR_{ti} ima vrednost 0,00516 m^2.h.°C/kJ.

[2] V tem času se temperatura na površini telesa zniža s 33 °C na 32 °C in srednja temperatura telesa s 36,6 °C na 35 °C; ΔR_{ti} ima vrednost 0,00258 m^2.h.°C/kJ.

[3] V tem času se temperatura kože na površini ztniža s 33 °C na 30 °C in srednja temperatura telesa s 36,6 °C na 32 °C; ΔR_{ti} ima vrednost 0,00774 m^2.h.°C/kJ.

*** Območje ugodja, v katerem enačba 12 ni enoznačna, ker je rezultat 0/0, oseba se naprej ne ohlaja.

[1] during this time the temperature on the body surface decreases from 33 to 30 °C and the body mean temperature from 36.6 to 33 °C; ΔR_{ti} has the value 0.00516 m^2.h °C/kJ;

[2] during this time the temperature on the body surface decreases from 33 to 32 °C and the body mean temperature from 36.6 to 35 °C; ΔR_{ti} has the value 0.00258 m^2.h°C/kJ;

[3] during this time the temperature on the body surface decreases from 33 to 30 °C and the body mean temperature from 36.6 to 32 °C; ΔR_{ti} has the value 0.00774 m^2.h °C/kJ;

*** the zone of comfort in which Equation 12 is not defined due to the result 0/0. A person is not cooling down anymore.

5.0 SKLEPI

Iz opisa pristopa k razvoju metode je razvidna kompleksnost postopka za ugotavljanje časa tolerance. Na čas tolerance vplivajo številni parametri, ki v večini primerov nimajo konstantne vrednosti. Vrednosti nekaterih parametrov lahko vzamemo iz obsežne literature, v kateri se obravnavajo bolj specifični problemi. Osnovni problem je posplošitev rezultatov tako, da bi jih komponirali v celoto, ki bi pomenila možnost dovolj natančne ocene adekvatnosti uporabe določenega kompleta oblačila v natančno definiranih razmerah sistema človek, oblačilo, okolje. Metoda ugotavljanja časa tolerance v tem delu je sestavljena iz več metod, ki skupaj pomenijo uporabnost in dostopnost uporabe metode v realnem življenju širšemu krogu specifičnih skupin in posameznikov. Posledice tega bi bilo zmanjšanje poškodb posameznikov in celo ohranitev življenj pri delovanju v ekstremnih razmerah.

5.0 CONCLUSION

The approach to the development of the method described in the paper shows how difficult and complex endeavour is to determine the tolerance time. Lots of parameters, which in most cases do not have constant values, influence the tolerance time. The values of certain parameters can be found in extensive literature, which deals with more specific problems. The main problem is generalization of the results so that they could be composed in a whole, which would enable quite precise estimation of the adequacy of a certain set of clothing in exactly defined man-clothing-environment systems.

In this study, the method is composed of several methods, which together mean applicability and availability of the method in real life for a wider circle of specific groups or individuals. The result is less injuries and more saved lives in extreme conditions.

Viri / References

[1] KERSLAKE. D. MCK. *Textile for comfort*. Manchester : Shirley Institute, 1971.

[2] JAKŠIĆ, D. Effect of the parameters of environment and shape of clothing surfaces on their thermal resistance. *Journal of Textile Institute*, 2004, vol. 95, no. 1/6, p. 183–186.

[3] JAKŠIĆ, D. Možnosti določanja poroznosti ploskovnih tekstilij = Possibility of the porosity determination of flat textiles. *Tekstilec*, 1994, let. 37, št. 7/8, str. 221–228.

[4] FORSTER et al. Am.J.Physiol., 1946, vol. 146, p. 600.

[5] JAKŠIĆ, D. *Projektiranje in konstrukcija tekstilij*. Ljubljana : VTOZD Tekstilna tehnologija, 1988, str. 161–167.

[6] CICENKO, GV. *Sbornik Naučno-issledovateljskih trudov*, 1963, CNIIŠP, No. 13.

[7] NEWBURG, LH. Et al. *Physiology of Heat Regulation and The Science of Clothing*. New York; London : Hafner Publishing Co., 1968, p. 115.

[8] GRANT RT. et al. *Clin.Sc.*, 1938, vol. 3, p. 373.

[9] BARTON, AC. *J. Nutration*, 1935, vol. 9; p. 261.

[10] BÜTTNER, K. *Physikalische Bioklimatologie*. Leipzig, 1938.

[11] WELAN, M. et al. *Textile Research Journal*, 1955, vol. 3, p. 210.

[12] JAKŠIĆ, D. Analitična metoda ugotavljanja upora pretoku vodne pare skozi ploske tekstilije. *Tekstilec*, 1988, vol. 31, štev. 5, str. 169–178.

[13] JAKŠIĆ, D. *Razvoj zaščitnega oblačila proti bojnim strupom : interna dokumentacija*. Ljubljana : VTO Oddelka za tekstilstvo, 1988.

[14] KOLESNIKOV, PA. *Teplozaščitnie svojstva odeždi*. Moskva : Legkaja industrija, 1965, p. 13.

[15] NEWBURGH, LH. *Physyology of heat regulation and the science of clothing*. New York; London : Hafner Publishing Co., 1968, p. 377–386.

Prispelo/Received: 07-2006; sprejeto/accepted: 11-2006