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Analysis of the Energy Balance in the System Human – Clothing – Environment

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Introduction

Human feels the best when his body is in the thermal comfort. Heat or energy balance can be achieved when the human organism generates so far energy so can be transferred in the relation with the environment. The factors which can take influence to the energy balance are these [1]:

1) environmental factors:
- air temperature;
- air velocity rate;
- mean radiant temperature;
- humidity.

2) human personal factors:
- activity;
- clothing insulation;
- spending time in researching environment.

System Human – clothing – environment includes all these factors assessment. The human body cooling methods who is situated in the hot environment was analyzed in [2]. Thermoelectric cooling was chosen from all presented methods. If we want to integrate this cooling system into human wearing clothes first of all we have to find how much excess of heat needs to be eliminated from the human body to reach energy balance. In this paper we will analyze the environmental, human wearing clothing and personal factors influence on the energy balance in the high temperature environment.

Equation of the energy balance

The general energy balance equation of the human body is [3, 4, 5]:

$$S = (M - W) - (R + C + E + K) - (C_{\text{res}} + E_{\text{res}}); \qquad (1)$$

here S – the heat storage rate; M – the metabolic energy production rate; W – the external mechanical work; R – the radiation heat loss from the skin; C – the convective heat loss from the skin; E – the evaporative heat loss from the skin; K – the conduction to the surfaces by direct contact with skin or clothing; C_{res} – the convective heat loss from respiration; E_{res} – the evaporative heat loss from respiration. All the components of the energy balance are measured W/m^2.

The metabolic rate M is defined as the rate at which the body utilizes food to produce energy. This rate is directly proportional to oxygen consumption dissipated from food in the basal body state (during absolute rest). The external mechanical work W for most activities can be made equal to zero. The energy balance components (M-W) describe heat production in the human body. The other components (R, C, E, K, C_{res}, E_{res}) describe heat consumption. The conduction K is usually very small relative to other terms and can safety be neglected.

Thermal energy balance is when the heat storage rate is equal to zero (S=0). When the heat storage rate S is positive (S>0) the body temperature increases and there is heat gain and the human body needs cooling and when it is negative (S<0) – decreases – there is heat loss and the body needs heating.

Radiative heat exchange R between the human body and environment:

$$R = h_{\text{r}} \cdot F_{\text{cl}} \cdot (T_{\text{sk}} - T_{\text{mrt}}); \qquad (2)$$

where h_{r} – radiative heat transfer coefficient (W/m^2·°C); F_{cl} – reduction factor for sensible heat exchange due to the clothes worn; T_{sk} – the skin temperature ($^{\text{o}}$C); T_{mrt} – the mean radiant temperature ($^{\text{o}}$C).

Reduction factor depends on wearing clothing insulation and it is equal:

$$F_{\text{cl}} = \frac{1}{(h_{\text{c}} + h_{\text{r}}) \cdot I_{\text{cl}} \cdot 0{,}155 + 1/f_{\text{cl}}}; \qquad (3)$$

here I_{cl} is intrinsic insulation of the clothing (clo); f_{cl} is clothing area factor; h_{c} is convective heat transfer coefficient (W/m^2·°C) depends from air velocity v_{a}:

$$h_{\text{c}} = 8{,}7 \cdot v_{\text{a}}^{0{,}6}. \qquad (4)$$

Clothing area factor f_{cl} relation with intrinsic insulation of the clothing I_{cl}:

$$f_{\text{cl}} = 1 + 0{,}31 \cdot I_{\text{cl}}. \qquad (5)$$

Radiative heat transfer coefficient can be found from the next equation:

$$h_r = k \cdot \varepsilon_p \cdot \frac{A_r}{A_{Du}} \cdot \frac{\left[(T_{sk}+273)^4 - (T_{mrt}+273)^4\right]}{T_{sk} - T_{mrt}}; \quad (6)$$

here k – Stefan-Boltzmann's constant ($5{,}67 \cdot 10^{-8}$ W/m$^2 \cdot$K^4); ε_p – emissivity of the human body (≈ 0,97); A_r/A_{Du} – the fraction of skin surface (≈ 0,77).

Convective heat loss from the skin:

$$C = \frac{(T_{sk} - T_a)}{R_{tdyn}}; \quad (7)$$

where T_a – the ambient temperature (^{o}C); R_{tdyn} – the dynamic thermal resistance of the clothing system (m$^2 \cdot ^o$C/W).

Dynamic thermal resistance of the clothing system R_{tdyn} depends on characteristics of wearing clothes and on environment: air velocity and human walking speed.

Evaporative heat loss from the skin is:

$$E = \frac{w \cdot (P_{sk} - P_a)}{R_{etdyn}}; \quad (8)$$

w – skin wettedness; P_{sk} – saturated vapor pressure at mean skin temperature (kPa); P_a – vapor pressure of the environment (kPa); R_{etdyn} – dynamic total water vapor resistance of the clothing system (m$^2 \cdot$kPa/W).

The saturation vapor pressure at a given temperature is calculated by Antoine's formula:

$$P_{sat} = 0{,}1333 \cdot e^{(18{,}6686 - 4030{,}183/(T+235))}. \quad (9)$$

Vapor pressure P_a depends from relative humidity and dynamic water vapor resistance of the clothing system. R_{etdyn} depends on wearing clothes and environment.

Convective heat loss from respiration:

$$C_{res} = 0{,}0014 \cdot M(34 - T_a). \quad (10)$$

Evaporative heat loss from respiration:

$$E_{res} = 0{,}0173 \cdot M(5{,}87 - P_a). \quad (11)$$

Analyzing the energy balance of the human body essential notice that some parameters depends on personal human characteristics, there are metabolic rate, mean skin temperature and surface area.

Metabolic rate M can be received using Harris – Benedict formulas [3]:

a) for males

$$M = 66 + 13{,}7 \cdot w + 5 \cdot h - 6{,}8 \cdot a; \quad (12)$$

b) for females

$$M = 655 + 9{,}6 \cdot w + 1{,}7 \cdot h - 4{,}7 \cdot a; \quad (13)$$

here w – human weight (kg); h – human height (m); a – human age (year).

Mean human surface area can be calculated by Du Bois & Du Bois formula:

$$A = 0{,}203 \cdot w^{0{,}425} \cdot h^{0{,}725}. \quad (14)$$

Mean skin temperature evaluating environment [6] is:

$$T_{sk} = 12{,}17 + 0{,}02 \cdot T_a + 0{,}044 \cdot T_{mrt} + 0{,}194 \cdot P_a - \\ - 0{,}253 \cdot v_a + 0{,}00297 \cdot M + 0{,}513 \cdot T_{re}. \quad (15)$$

In the next paragraph we have calculated the energy balance using (1) equation in the various environmental conditions.

Influence of the environmental variables in the energy balance

The basic environmental variables what can take effect on the human energy balance are ambient temperature T_a, mean radiant temperature T_{mrt}, air velocity v_a and relative humidity RH. There are shown the dependence of these parameters at various human activity levels in the figures 1-3. In these figures are analyzed four human activity levels:

1) 1 Met=58,2 W/m^2, sitting relaxed human;
2) 1,9 Met=110,58 W/m^2, walking on the rate 2 km/h;
3) 3,4 Met=197,88 W/m^2, walking on the rate 5 km/h;
4) 8,5 Met=494,7 W/m^2, running on the rate 7,5 km/h.

Fig. 1 shows the heat storage, which needs to eliminate from the human body for the thermal comfort at the different ambient temperature. Other conditions are following: T_{mrt} = 60° C, RH=20 %, v_a=0,3 m/s, I_{cl}=1 clo. At each activity level, the higher ambient temperature is, the more heat we need to eliminate from the body. Additionally, a higher metabolic rate is generated, the more heat storage accumulate in the body.

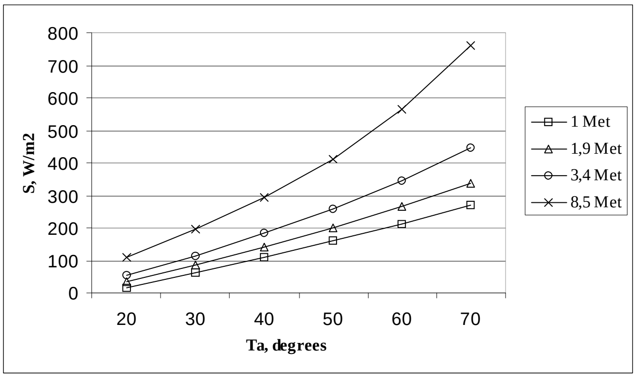

Fig. 1. Expected heat storage rate in the human body for various ambient temperature values

Fig. 2 shows the heat storage, which needs to eliminate from the human body for the thermal comfort at the different mean radiant temperature. Other parameters are following: T_a = 40 °C, RH=20 %, v_a=0,3 m/s, I_{cl}=1 clo. These dependences match to figure 1 in principle: the higher mean radiant temperature, the higher heat storage.

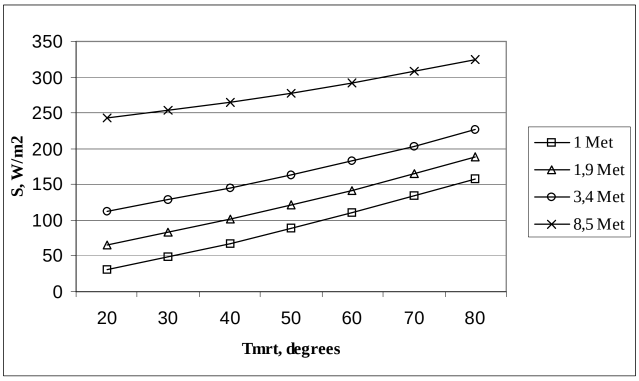

Fig. 2. Expected heat storage rate in the human body for various mean radiant temperature values

As shown in the Fig. 3 the bigger air velocity value is the excess of the heat storage decreases. This depends on convective and evaporative heat exchange, while air velocity increases, these two components of the thermal energy balance increase, too. Other environmental parameters are following: T_a = 40° C, T_{mrt} = 60° C, RH=20 %, I_{cl}=1clo. A higher metabolic rate is generated the more heat storage is needed to compensate in the body for the thermal comfort. At the biggest activity level 8,5 Met and when the air velocity are 5 m/s and 8 m/s the heat storage begin to rise. This appearance comes from that: convective and radiative heat exchange decreases and evaporative heat loss begin to decrease too.

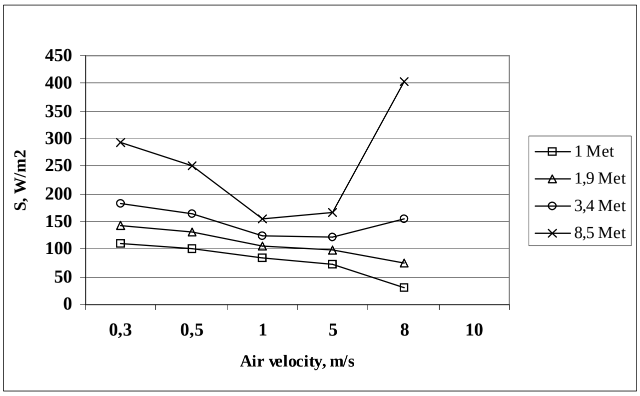

Fig. 3. Expected heat storage rate in the human body for various values of air velocity

Influence of the clothing on the energy balance

One of the most important parameters of the human wearing clothing is clothing insulation. As depicted in the figure 4 the more clothes (or clothes with the higher clothing insulation) is wearing human in hot environment where T_a = 40°C, T_{mrt} = 60°C, RH=20%, v_a=0,3m/s, the less heat storage needs to eliminate from the body at low activity level. At very high activity level (8,5 Met) heat storage rate increases. This can be explained so: the more clothes the less heat human can eradiate into environment at the low activity level.

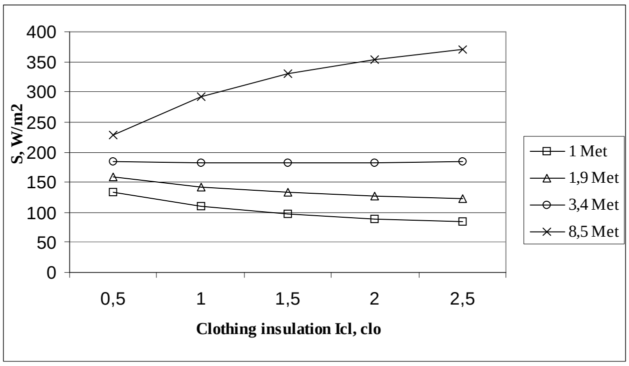

Fig. 4. Expected heat storage rate in the human body for various values of clothing insulation

The body temperature rate dependence on ambient temperature

When we have the human energy balance we can get how much degrees temperature increases or decreases in the human body in special environmental conditions. In other words, we can get how long time human exposure in such environment won't make any influence or any side-effect. So, the body temperature change [3] along a time unit (°C/s) is calculated by this equation:

$$\frac{\Delta T}{dt} = \frac{S \cdot A}{m \cdot 3{,}49 \cdot 10^3}; \qquad (16)$$

where S is the heat storage rate; A is human surface area (14); m is human mass and 3,49 kJ/(kg·K) is specific heat requirements.

Human exposure time dependence on different ambient temperature is depicted in the figure 5. Here is shown how much time human can spend in the hot environment while his body temperature rises 1°C at the various activity levels. This dependences are calculated for the human who's personal characteristics are those: weight 70 kg, height 1,70 m, surface area 1,8 m^2. For example, when the air temperature is 30°C, other parameters are T_{mrt} = 60°C, RH=20%, v_a=0,3m/s, I_{cl}=1clo, the sitting relaxed man can safety spend in that environment about 36 minutes, his body temperature rises only 1°C and this is not so dangerous. But when air temperature rises up to 60°C here he can be not more then 10,6 minutes. The higher activity level the less time human can work in hot environment.

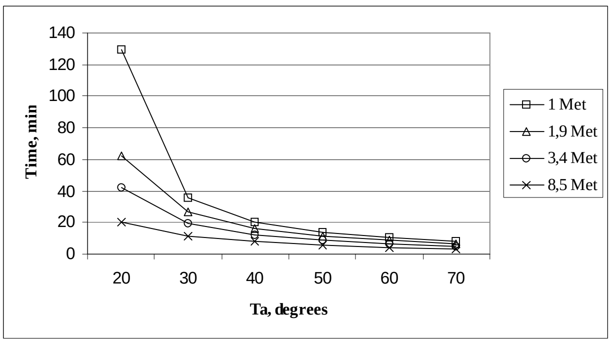

Fig. 5. Human exposure time dependence on the different ambient temperature

Conclusions

1. Environmental factors (air temperature, air velocity, mean radiant temperature, humidity), personal human factors (activity, wearing clothes) and exposure time have influence on the energy balance.

2. The higher ambient temperature and mean radiant temperature the higher heat storage needs to be eliminated from the human body.

3. Vice versa the bigger air velocity value is the excess of the heat storage decreases.

4. The higher activity level the less time human can safety work in hot environment.

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In the system human – clothing – environment is researching correlation between these three factors. There is presented the energy balance equation in the human body, expressions of it components and analysis. There is analyzed influence of the environmental factors: ambient temperature, mean radiant temperature, air velocity and human wearing clothes insulation to the energy balance. Dependences on heat storage of some parameters are presented on the various environmental conditions and on the various activity level: sitting relaxed, walking on the rate 2 km/h, walking on the rate 5 km/h, running on the rate 7,5 km/h. These figures show how much heat storage needs to be eliminated from the body for the thermal comfort. At the same activity level is got dependence indicative of the variation rate of the human body temperature. Ill. 5, bibl. 6 (in English; summaries in English, Russian and Lithuanian).

С. Барткявичюс, Р. Рачкене, Ю. А. Вирбалис. Анализ энергетического баланса в системе человек – одежда – окружающее пространство // Электроника и электротехника. – Каунас: Технология, 2008. – № 7(87). – С. 61–64.

В системе одежда – человек – окружающее пространство рассматривается взаимосвязь всех трех составляющих частей. Представлено уравнение энергетического баланса человеческого тела, его анализ и выражение его составляющих. Обсуждено влияние на энергетический баланс внешних факторов: окружающей температуры, температуры радиации, скорости ветра, а также изоляционных свойств одежды. Представлены зависимости суммарной тепловой мощности от различных параметров окружающей среды при различной физической активности человека: спокойно сидящего, идущего со скоростью 2 km/h, идущего со скоростью 5 km/h ir бегущего со скоростью 7,5 km/h. Из этих зависимостей видно, сколько избыточной тепловой энергии нужно рассеять для удовлетворения уравнения энергетического баланса. При той же активности получена зависимость показывающая скорость изменения температуры тела человека. Ил. 5, библ. 6 (на английском языке; рефераты на английском, русском и литовском яз.).

S. Bartkevičius, R. Račkienė, J. A. Virbalis. Energijos balanso analizė žmogaus, aprangos ir aplinkos sistemoje // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2008. – Nr. 7(87). – P. 61–64.

Žmogaus, aprangos ir aplinkos sistemoje nagrinėjamas šių trijų veiksnių tarpusavio ryšys. Pateikta žmogaus kūno energijos balanso lygtis, jos dedamųjų išraiškos ir analizė. Išnagrinėta aplinkos veiksnių: aplinkos temperatūros, spinduliavimo temperatūros, vėjo greičio ir žmogaus dėvimų drabužių izoliacijos, įtaka energijos balansui. Pateiktos šiluminės galios priklausomybės nuo kai kurių parametrų, esant įvairioms aplinkos sąlygoms ir įvairiam žmogaus aktyvumui: ramiai sėdinčiam, einančiam 2 km/h greičiu, einančiam 5 km/h greičiu ir bėgančiam 7,5 km/h greičiu. Iš jų matyti, kiek šilumos pertekliaus reikia pašalinti iš organizmo, kad būtų tenkinamas energijos balansas. Tam pačiam aktyvumui gauta priklausomybė, rodanti žmogaus kūno temperatūros kitimo greitį. Il.5, bibl.6 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).