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The Effect of Thermal Insulation of Clothing on Human Thermal Comfort

Abstract
The human body is under various continuous external conditions, some of which make wearers uncomfortable. Usually, human thermal comfort depends on combinations of clothing, climate, and physical activity. Specifically thermal insulation in clothing is an important parameter of thermal comfort. Therefore, this paper discusses theoretically the basic physical principles of the body's mechanism for heat transfer with the environment. In this study, the body's heat balance was examined, and the effects of clothes and various climatic conditions on thermal comfort were investigated for different physical activities.

Key words: *clothing insulation, thermal comfort, physical activity, climatic conditions.*

Designations

- A_b area of body surface, m^2
- A_D area of body surface, m^2
- C heat loss by convection, W/m^2
- C_k heat loss by thermal conduction, W/m^2
- C_{res} sensible heat loss due to respiration, W/m^2
- E_{res} evaporative heat loss due to respiration, W/m^2
- E_{sk} heat loss by evaporation from the skin, W/m^2
- f_{cl} clothing area factor, clo
- F_{vf} viev factor between body and surrounding
- h body height, m
- h_c coefficient of convection heat transfer, W/m^2K
- I_{cl} thermal insulation of clothing, clo
- I_{cli} individual resistances of various garment, clo
- M metabolic rate (internal energy production), W/m^2
- Pa partial vapour pressure, Pa
- Ps saturation pressure of water vapor, Pa
- R heat loss by thermal radiation, W/m^2
- R_{cl} insulation of clothing, m^2K/W
- T_a ambient air temperaure, °C
- T_{cl} clothing surafce temperaure, °C
- T_r radiant temperaure, °C
- T_{sk} skin temperaure, °C
- V_a air velocity, m/s
- w body weight, kg
- W external work, W/m^2
- RH relative humidity, %
- ε_{cl} emmisivity of clothing
- σ Stefan-Boltzmann constant, W/m^2K^4.

Introduction

The human body is affected by various external conditions in the winter and summer seasons. These external conditions can include changes in ambient temperature, vapour pressure, air velocity, and clothing insulation, among other factors that affect skin temperature [21]. On the other hand, the body continuously produces heat, which must be transferred to the environment. People sometimes feel uncomfortable as a result of some of their physical activities due to the change of external conditions.

The temperature and humidity of the environment may profoundly influence the body's skin and interior temperature [22]. The human body is adapted to function within a narrow temperature range. Generally, the human body keeps its body temperature constant at 37 ± 0.5 °C under different climatic conditions.

Human thermal comfort depends on combinations of clothing, climate, and physical activity [13]. The human body converts the chemical energy of its food into work and heat. The amount of heat generated and lost varies markedly with activity and clothing levels [19].

The heat produced is transferred from the body's skin to the environment. In a steady-state heat balance, the heat energy produced by the metabolism equals the rate of heat transferred from the body by conduction, convection, radiation, evaporation and respiration [17].

Therefore, clothing is needed to protect the body against climatic influence and to assist its own thermal control functions under various combinations of environmental conditions and physical activities [13].

The heat loss from the body and the feeling of individual comfort in a given environment is much affected by the clothing worn [15]. However, of the copious research work carried out considering different aspects of human thermal insulation by clothing, elaborations which generalise this problem have been very rare. The aim of this study was to analyse theoretically the general, material dependencies between heat generation by humans and their heat losses considering various types of activity under different conditions, on the bases of well-known laws and equations, as well as of available experimental data concerning thermal property values.

In the study, the role of clothing in the thermal balance of the human body and thermal comfort under steady-state conditions have thus been investigated for various climatic conditions and different physical activities.

Heat exchanges of human body with environment

The body converts the chemical energy of its food into work and heat, producing through its processes of metabolism a great deal of heat. The amount of heat produced depends on the degree of activity [9]. The living body continuously produces heat which must be transferred to the environment. The expulsion of body heat primarily occurs from the body's surface. Through blood circulation, heat is transported to the skin, from which it is transferred to the environment [22].

In a steady-state heat balance, the heat energy produced by metabolism equals the rate of heat transferred from the body by conduction, convection, radiation evaporation and respiration [17].

The fundamental thermodynamic process in heat exchange between man and his environment may be described by the general heat balance equation (for the per-unit body surface area) [1, 4, 8, 10].

$$M - W = C + R + E_{sk} + (C_{res} + E_{res}) + C_k \quad (1)$$

The external work (W) in the equation is small, and is generally ignored under most situations. The internal energy production (metabolic rate) is determined by metabolic activity. Table 1 shows the rate of body heat production for an average male for different types of activity [4].

Table 1. *Typical metabolic heat generation for various activites [4].*

Activity	Heat generation, W/m^2
Resting	
Sleeping	40
Reclining	45
Seated, quiet	60
Standing, relaxed	70
Walking (on the level)	
0,89 m/s	115
1,34 m/s	150
1,79 m/s	220
Office activities	
Reading	55
Writing	60
Typing	65
Filing, seated	70
Filing, standing	80
Walking about	100
Lifting/packing	120
Miscellaneous occupational activities	
Cooking	90-115
House cleaning	115-120
Seated, heavy limb movement	130
Machine Work	
Sawing (table saw)	105
Light (electrical industry)	115-140
Heavy	235
Handling 50 kg bags	235
Pick and shovel work	235-280
Miscellaneous leisure activities	
Dancing, social	140-225
Tenis, singles	210-270
Basketball	290-440

Clothing slows down the rate of conduction, and the nature of the clothing influences the rate of conduction loss (C_k). The conduction heat loss is usually insignificant. Also, the rate of change of heat stored in the body is neglected in a steady-state heat transfer with its environment [22].

Since heat exchange, whether by radiation, convection, or vaporisation, is always related in some way to the body surface area A_b, it is convenient to describe each term in Equation (1) in terms of energy per unit area of body surface. The most useful measure of body surface area, proposed by Du Bois, is described thus:

$$A_D = 0.202 \cdot w^{0.425}\ h^{0.725} \qquad (2)$$

where the Du Bois surface (A_D) is in square meters, body weight (w) in kilograms, and height (h) in metres [1].

Convection

The convection heat transfer from the human body to the environment is given [4, 8, 6].

$$C = f_{cl} \cdot h_c \cdot (T_{cl} - T_a) \qquad (3)$$

The heat transfer coefficient h_c depends on the air velocity across the body, and consequently also upon the position of the person and orientation to the air current [17]. An approximate value of h_c during forced convection can be evaluated from the definition given in [1] as

$$h_c = 12.1 \cdot V_a^{0.5} \qquad (4)$$

where V_a is the air velocity. The clothing area factor (f_{cl}) in Equation (3) is expressed as follows [2]:

$$f_{cl} = 1.05 + 0.1\ I_{cl} \qquad (5)$$

where I_{cl} is the thermal insulation of clothing. Values of thermal insulation of clothing (I_{cl}) for some typical clothing ensembles are given in Table 2, and individual resistances of various garment (I_{cli}) are given in Table 3 [1, 2]. The thermal resistances proposed for individual items are listed in Table 3, to be combined by means of the following Equations (6) or (7) [11, 5]:

$$\text{clo-value (men)} = 0.727 \sum I_{cli} + 0.113 \quad (6)$$

$$\text{clo-value (women)} = 0.770 \sum I_{cli} + 0.050 \quad (7)$$

The human body is insulated against heat gains or losses by clothing. The insulation of clothing is often expressed in clo units, but it is used in SI units (R_{cl}) in calculations. The relationship between R_{cl} and I_{cl} is

$$R_{cl} = 0.155\ I_{cl} \qquad (8)$$

Radiation

The rate of heat transfer by radiation depends on the mean temperature of surrounding surfaces, skin or clothing surface temperature and properties of clothing (or skin) and surrounding surfaces. The radiation heat transfer between the body and surrounding surfaces is given as follows [4, 6, 8]:

Table 2. *I_{cl} and R_{cl} values of typical clothing ensembles [1].*

Clothing ensemble	I_{cl}, clo	R_{cl}, m^{2}K/W
MEN		
Cool socks, briefs, shoes, s.s. woven shirt, cool trousers	0.42	0.065
Warm socks, briefs, shoes, s.s. woven shirt, cool trousers	0.42	0.065
Cool socks, briefs, shoes, s.s. cool knit shirt, cool trousers	0.55	0.085
Cool socks, briefs, undershirt, shoes, i.s. woven shirt, cool trousers	0.51	0.079
Cool socks, briefs, undershirt, shoes, s.s. woven shirt, warm jacket, cool trousers0	0.73	0.113
Cool socks, briefs, shoes, cool trousers	0.31	0.048
Cool socks, briefs, undershirt, shoes, s.s. woven shirt, warm jacket, warm trousers	0.77	0.119
WOMEN		
Cool dress, pantyhose, bra and panties, shoes	0.21	0.032
Cool s.s. sweater, cool dress, pantyhose, bra and panties, shoes	0.30	0.046
Warm dress, pantyhose, bra and panties, shoes	0.49	0.076
Warm skirt, warm i.s. blouse, pantyhose, bra and panties, shoes	0.41	0.063
Warm i.s. sweater, warm skirt, warm i.s. blouse, pantyhose, bra and panties, shoes	0.64	0.099
Warm i.s. sweater, warm slacks, warm i.s. blouse, pantyhose, bra and panties, shoes	0.77	0.119
Warm i.s. sweater, warm slacks, pantyhose, bra and panties, shoes	0.59	0.091

Table 3. *Individual insulation values of men's and women's garments [1].*

MEN			WOMEN		
Garment	I_{cli}, clo	R_{cl}, m^{2}K/W	Garment	I_{cli}, clo	R_{cl}, m^{2}K/W
Cool socks	0.03	0.004	Bras and panties	0.05	0.007
Warm socks	0.04	0.006	Pantyhose	0.01	0.001
Briefs	0.05	0.007	Girdle	0.04	0.006
T-shirt	0.09	0.014	Half slip	0.13	0.020
Undershirt	0.06	0.009	Full slip	0.19	0.029
Woven s.s. shirt	0.19	0.029	Cool dress	0.17	0.026
Woven i.s. shirt	0.29	0.045	Warm dress	0.63	0.097
Cool s.s. knit shirt	0.22	0.034	Warm i.s. blouse	0.29	0.045
Warm s.s. knit shirt	0.25	0.038	Warm skirt	0.22	0.034
Cool i.s. knit shirt	0.14	0.021	Cool i.s. blouse	0.20	0.031
Warm i.s. sweater	0.37	0.057	Cool slacks	0.26	0.040
Warm jacket	0.49	0.076	Warm slacks	0.44	0.068
Cool trousers	0.26	0.040	Cool sleeveless sweater	0.17	0.026
Warm trousers	0.32	0.049	Warm i.s. sweater	0.37	0.057
Shoes	0.04	0.006	Cool s.s. sweater	0.17	0.026

$$R = \sigma \cdot \varepsilon_{cl} \cdot f_{cl} \cdot F_{vf} \left[(T_{cl} + 273.15)^4 + - (T_r + 273.15)^4\right] \quad (9)$$

where ε_{cl} is emissivity of the clothing. The emissivity of the clothing and skin is very close to that of a black body, and thus has a value of nearly 1. The effective area of the body for radiation is consequently less than the total surface area, usually about 75 percent of the total [17]. The effective area is determined with the view factor between the body and surrounding surface (F_{vf}). σ is the Stefan-Boltzmann constant, which has the numerical value of 5.67×10^{-8} W/m^{2}K^4. The surrounding surface temperature is usually at a low temperature level. Thus the temperatures of the surrounding surfaces can be taken as approximately ambient air temperature.

Respiration

The respiration heat loss is divided into evaporative heat loss (latent heat) and sensible heat loss. The rate of heat transfer by respiration is usually at the lower level beside the other rates of heat transfer.

The calculation of this rate of heat loss has been defined in reference works [1, 2]. The rate of this transfer is given by:

$$C_{res} + E_{res} = 0.014\, M\, (34 - T_a) + + 0.0173\, M\, (5.87 - P_a) \quad (10)$$

where P_a is the partial vapour pressure. The partial vapour pressure is calculated using the following equation:

$$RH = P_a / P_s \quad (11)$$

where RH is the relative humidity of the ambient air and P_s is the saturation pressure of water vapour. The saturation pressure of water vapour is calculated as follows [16]:

$$P_s = [0.782 + 2.962(T_a/100) + + 6.290(T_a/100)^{2.325}]^2 \quad (12)$$

Evaporation from the skin

The rate of heat loss by evaporation is the removal of heat from the body by the evaporation of perspiration from the skin. Evaporation always constitutes a rejection of heat from the body [17]. The evaporation loss is dependent upon the mass transfer coefficient and the air humidity ratio for a given body surface temperature [22]. The heat loss by evaporation is made up of two, the insensible heat loss by skin diffusion, and the heat loss by regulatory sweating. The calculation of this rate of heat loss has been defined in references [1, 2, 17]. This rate of heat loss can be calculated by:

$$E_{sk} = 3.05\, [5.73 - 0.007\, M - P_a] + + 0.42\, [M - 58.15] \quad (13)$$

Clothing surface temperature

Figure 1 shows the heat energy flow through the clothing. The conduction heat transfer through the clothing takes place in order to the different temperatures of its inner and outer surfaces.

The conduction heat transfer from the inner surface to the outer surface of the clothing is defined as follows:

$$C_k = (T_{sk} - T_{cl}) / R_{cl} \quad (14)$$

This heat transfer from the clothing's outer surface is further transferred to the environment by convection and radiation heat losses.

$$C_k = C + R \quad (15)$$

As the heat energy flow through the clothing in the steady-state is determined by (14), the clothing temperature can be determined from Equations (14) and (15) as:

$$T_{cl} = T_{sk} - R_{cl}\, (C + R) \quad (16)$$

where T_{cl} is the temperature of the outer surface of the clothing. The clothing temperature can be rewritten using Equations (3) and (9).

$$T_{cl} = T_{sk} - R_{cl} \{f_{cl} \cdot h_c \cdot (T_{cl} - T_a) + + \sigma \cdot \varepsilon_{cl} \cdot f_{cl} \cdot F_{vf} [(T_{cl} + 273.15)^4 + - (T_r + 273.15)^4]\} \quad (17)$$

The clothing temperature can be solved by applying the fixed-point iteration.

Where T_{sk} is the mean temperature of the body skin. The skin temperature is defined as follows [1, 4, 10]:

$$T_{sk} = 35.7 - 0.0275\, M \quad (18)$$

Considering these assumptions, we may state that this 'skin temperature' is an average contractual value.

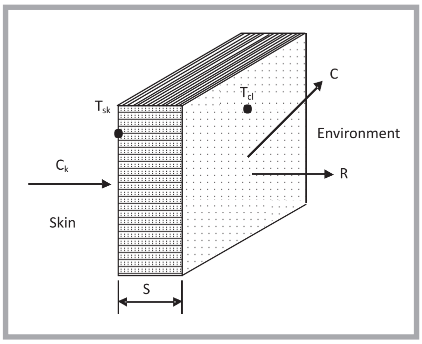

Figure 1. The heat energy flow through the clothing; R - heat loss by thermal radiation, W/m^2, C - heat loss by convection, W/m^2, C_k - heat loss by thermal conduction, W/m^2 (the heat steam from the body (skin) through the clothing), T_{sk} - skin temperature, ^{o}C, S - thickness.

Results and discussion

The total heat transfer from the body includes the heat that is transferred by the exposed skin and the heat passing through the clothing [14]. Human thermal comfort is influenced not only by ambient air temperature and humidity, but also by the rate of air velocity, physical activity, and properties of clothing [22].

Figure 2 shows the variation of the heat losses from the body with the metabolic rate. The increase in the metabolic rate leads to a decrease in the convection and radiation heat losses, but the evaporation heat loss increases with the higher metabolic rate.

The variation of heat losses from the body with the ambient air temperature is shown in Figure 3. The air temperature is an important environmental factor. Specifically, it determines the amounts of the convection heat loss and evaporation heat loss. The decrease in the difference between the clothing surface temperature (or skin

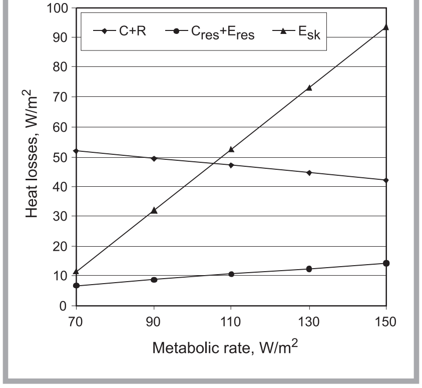

Figure 2. The variation of heat losses from the body with the changes of metabolic rate (I_{cl}=0.75 clo, T_a=22 °C, V_a=0.1 m/s, RH=50%).

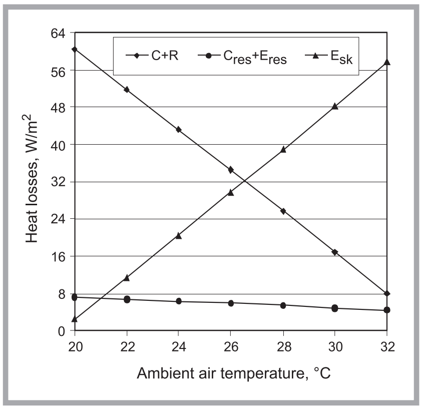

Figure 3. The variation of heat losses from the body with the ambient air temperature (M=70W/m^2, I_{cl}=0.75 clo, V_a=0.1 m/s, RH=50%).

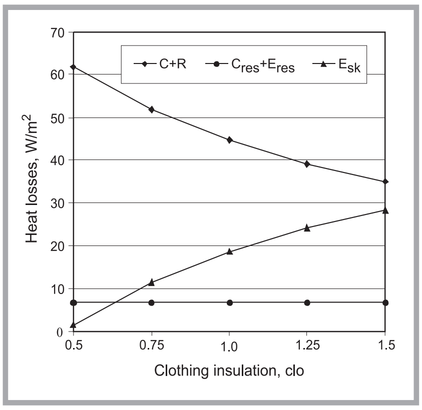

***Figure 4.** The variation of heat losses from the body with clothing insulation (M=70 W/m², T_a=22 °C, V_a=0.1m/s, RH=50%).*

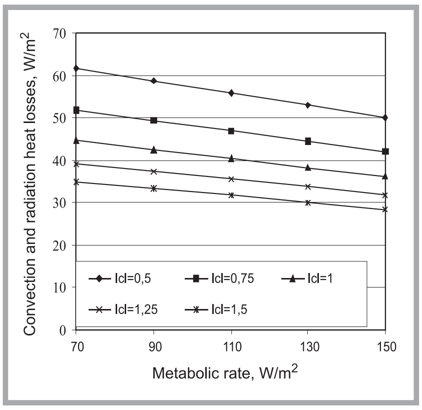

***Figure 5.** The variation of convection and radiation heat losses from the body with the metabolic rate for different clothing insulations (T_a=22 °C, V_a=0.1 m/s, RH=50%).*

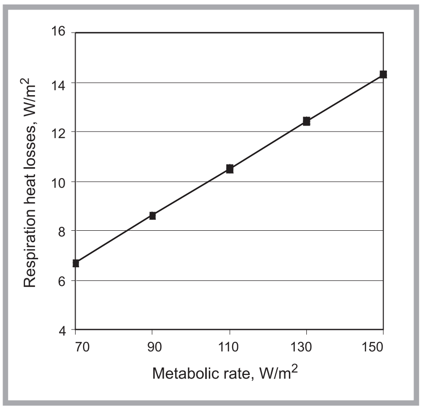

***Figure 6.** The variation of respiration heat losses from the body with the metabolic rate for all the clothing insulations (T_a=22 °C, V_a=0.1 m/s, RH=50%).*

temperature) and the ambient air temperature is caused by changing the heat losses by convection and radiation. As seen in the figure, the increase in the ambient air temperature decreases the convection and radiation heat losses. Also, the higher values of ambient air temperature cause increases in the evaporation heat loss.

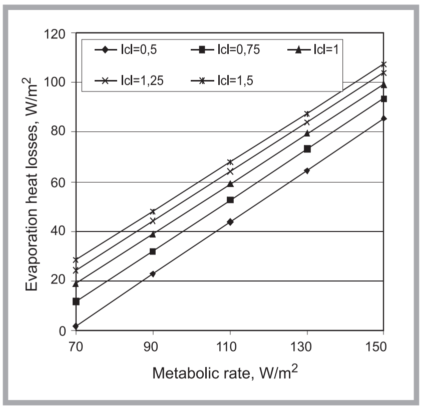

***Figure 7.** The variation of evaporation heat loss from the skin with the metabolic rate for different clothing insulations (T_a=22 °C, V_a=0.1 m/s, RH=50%).*

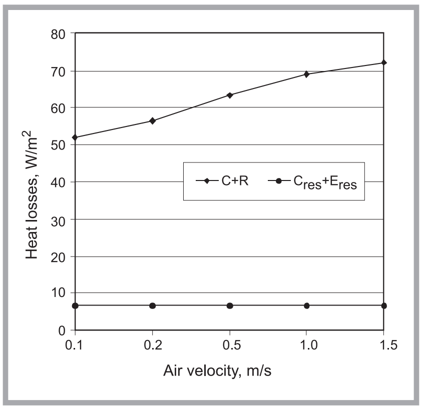

***Figure 8.** The variation of heat losses from the body with the air velocity (M=70 W/m², I_{cl}=0.75 clo, T_a=22 °C, RH=50%).*

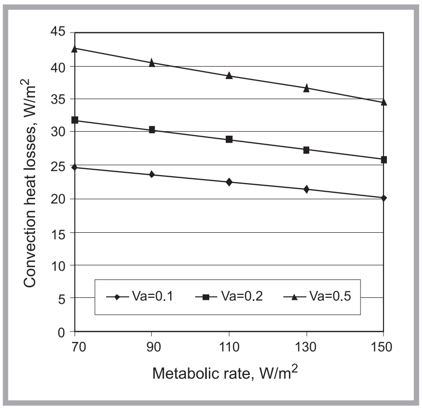

***Figure 9.** The variation of convection heat loss from the body with the metabolic rate for different air velocity (T_a=22 °C, I_{cl}=0.75 clo, RH=50%).*

Figure 4 shows the variation of the heat losses from the body with the clothing insulation. Thermal insulation is a very important factor for estimating garment comfort for the user [7]. As seen in the figure, convection and radiation heat losses decrease with the increase in the clothing insulation.

The variation of convection and radiation heat losses, respiration heat losses and evaporation heat loss with the metabolic rate for different clothing insulation are shown in Figures 5 - 7. It can be seen that as the metabolic rate increases, the convection and radiation heat losses from the body decrease. Also, higher values of clothing insulation cause the heat losses to decrease. As seen, the respiration and the evaporation heat losses increase with the increase in the metabolic rate. However, the respiration heat losses do not change with the clothing insulation.

The variation of heat losses from the body with the air velocity is shown in Figure 8. The higher air velocity leads to higher heat transfers at the surface of exposed skin and to local cooling of the skin. Normal room temperatures (20 to 22 °C) and acceptable air velocities of 0.1 to 0.2 m/s are given [20]. It can be seen that the air velocity is affected by the convection and radiation heat losses.

The variation of convection, radiation and evaporation heat losses with the metabolic rate for different air velocity are shown in Figures 9 - 11. As seen in the figures, the convection and the radiation heat losses decrease and the evaporation heat loss increases with an increase in the metabolic rate. Also, the increase in the air velocity leads to an increase in the convection heat loss and decreases the radiation and evaporation heat losses.

Figure 12 shows the variation of heat losses from the body with the ambient air relative humidity. As seen, the heat losses are not much changed by the ambient air relative humidity.

The variation of convection and radiation heat losses, respiration heat losses and evaporation heat loss with the metabolic rate for different ambient air relative humidities are shown in Figures 13 - 15. As seen in the figures, the convection and radiation heat losses decrease and the respiration heat losses and the evaporation heat losses increase with the increase in the metabolic rate. The respiration heat losses also decrease with the higher relative humidity values. However, the convection and radiation heat losses and the evaporation heat losses are not much changed by the relative humidity.

The variation of the clothing surface temperature and the temperature of the body skin with the metabolic rate for the

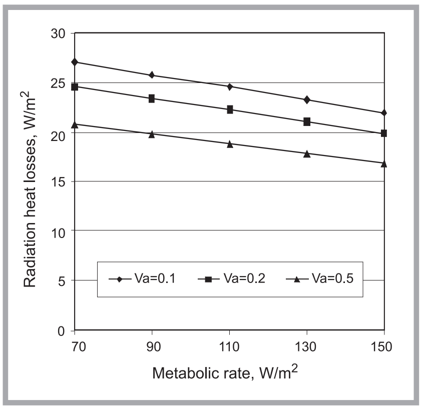

***Figure 10.** The variation of radiation heat loss from the body with the metabolic rate for different air velocity (T_a=22 °C, I_{cl}=0.75 clo, RH=50%).*

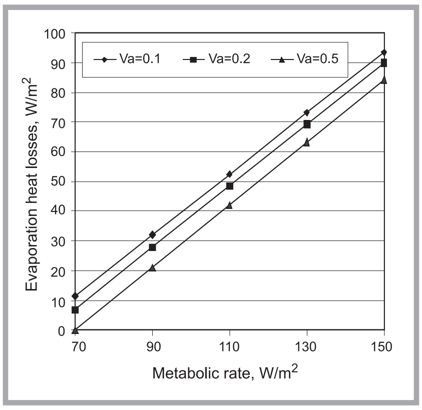

***Figure 11.** The variation of evaporation heat loss from the skin with the metabolic rate for different air velocity (T_a=22 °C, I_{cl}=0.75 clo, RH=50%).*

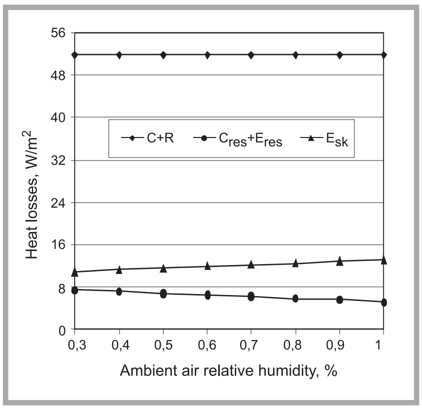

***Figure 12.** The variation of heat losses from the body with the ambient air relative humidity (M=70 W/m^2, I_{cl}=0.75 clo, T_a=22 °C, V_a=0.1 m/s).*

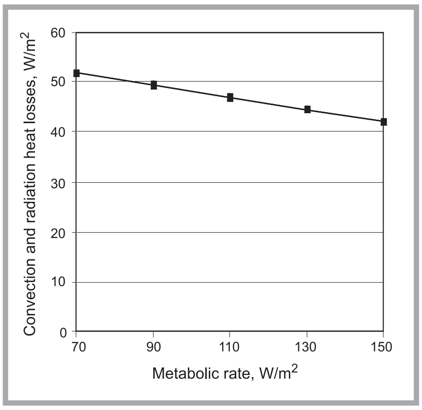

***Figure 13.** The variation of convective and radiative heat losses from the body with the metabolic rate for all the ambient air relative humidities (T_a=22 °C, V_a=0.1 m/s, I_{cl}=0.75 clo).*

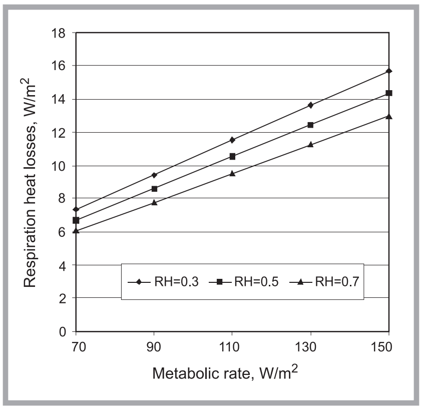

***Figure 14.** The variation of respiration heat losses from the body with the metabolic rate for different ambient air relative humidities (T_a=22 °C, V_a=0.1 m/s, I_{cl}=0.75 clo).*

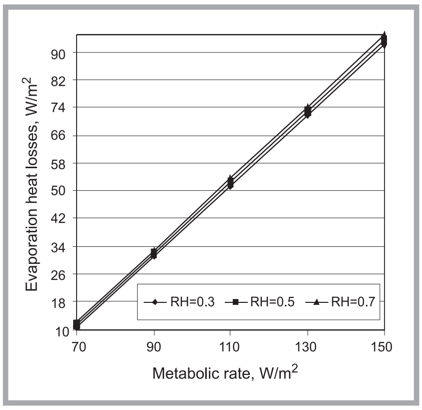

***Figure 15.** The variation of evaporation heat loss from the skin with metabolic rate for different ambient air relative humidities (T_a=22 °C, V_a=0.1 m/s, I_{cl}=0.75 clo).*

different clothing insulations are shown in Figure 16. As seen in the figure, the increase in the metabolic rate decreases the clothing surface temperature and the temperature of the body skin. Also, the higher values of clothing insulation reduces the clothing surface temperature.

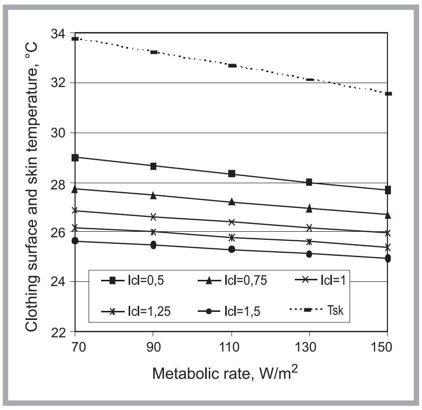

***Figure 16.** The variation of clothing surface temperature with the metabolic rate for different clothing insulations (T_a=22 °C, V_a=0.1 m/s, RH=50%).*

The increased metabolic activities causes a higher core temperature in the body. For this reason, when the activity level increases, the skin temperature must decrease for human thermal comfort. In the same environmental conditions, if the skin temperature of the body falls, heat losses from the body may increase [12]. In this way, the heat balance of the body is provided for any metabolic rate [3]. Also the decrease in the skin temperature leads to a decrease in the clothing surface temperature with a higher metabolic rate.

Summary

The human body continuously produces heat by its metabolic processes [18]. The heat is lost from the surface of the body by convection, radiation, evaporation and respiration.

In a steady-state situation, the heat produced by the body is balanced by the heat lost to the environment [21]. If not, the body temperature will increase and the human feels uncomfortable. Human thermal comfort depends on the metabolic rate (internal heat production), the heat losses from the body and the climatic conditions. As is well-known, the clothing properties (especially clothing insulation) are affected by these parameters.

Clothing reduces the body's heat loss. If the wearer is not to perspire in summer and feel cold in winter, they must wear appropriate garments for their thermal comfort. The wearer may consciously assist the body to maintain its proper heat balance under exposure conditions by wearing suitable clothing. Therefore, clothing insulation is very important for human thermal comfort.

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Received 26.01.2006 Reviewed 15.06.2006

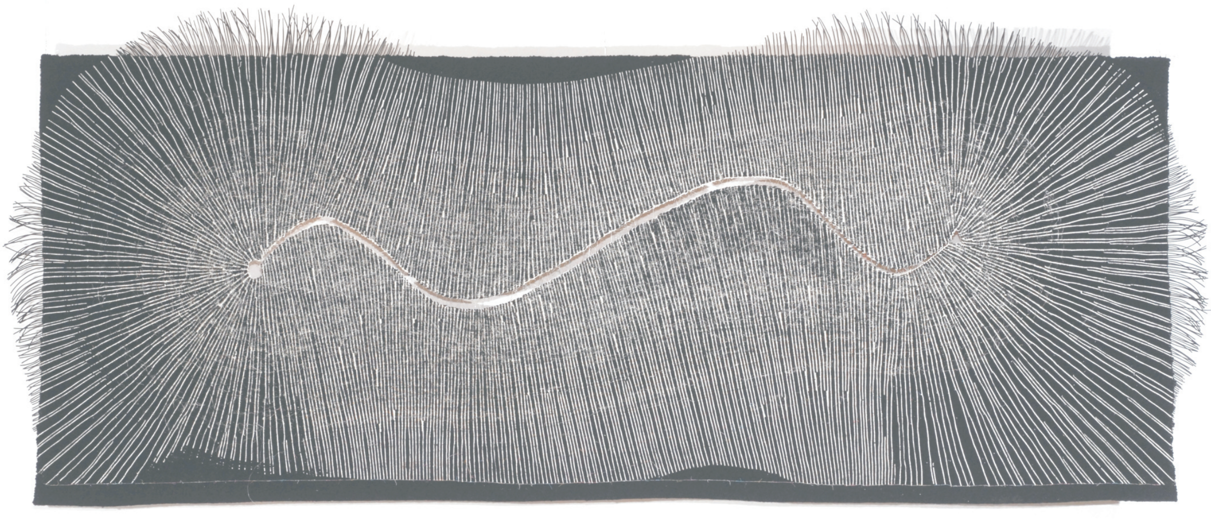
Latest news

On 21 May 2007 ***Professor Włodzimierz Cygan****, member of the* ***Editorial Committee of Fibres & Textiles in Eastern Europe****, former Associate Editor of the Fibre and Textile Art section was awarded the* ***Golden Medal*** *of the* ***12th International Triennial of Tapestry****, Łódź, Poland, the world's greatest textile art event for his wall-hanging entitled 'Orbitek'.*

Włodzimierz Cygan*, born in Łódź, graduated from the Strzemiński Academy of Fine Art and Design in Łódź. He is Professor at the Academy of Fine Art in Gdańsk and the Technical University of Łódź active at its Institute of Textile Architecture. He is also member of The Friends of Fibre Art International and of the Board of World Crafts Council – Poland.* ***Professor Włodzimierz Cygan*** *presented his works, in the majority made in the weaving technique, at numerous solo and group exhibitions in Poland, as well as in Austria, France, Germany, Hungary, Israel, Japan, Mexico, and the USA, awarding plenty of honorary mentions, medals, and prizes.*

We congratulate ***Professor Włodzimierz Cygan*** *on his international success and wish him much happiness and further continued creative successes.*

On behalf of all editors of the journal and the Institute's management
Bogdan Mac
Editor-in-Chief of Fibres & Textiles in Eastern Europe



Włodzimierz Cygan, 'Orbitek'*, 2006, wall-hanging, wool, sizal,polypropylene, size: 118 × 283 cm.*