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The Effect of Clothing on Thermoregulatory Responses of Human Body in a Hot Environment

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Abstract

Studying the effect of clothing on thermoregulatory responses of human body is highly complex because clothing, resp. a clothing system, as a heat exchange layer between the body and the environments must ensure a balance between heat production and heat dissipation within different environments and during various activities. The problem becomes more complex in the case of protective clothing, which requires liquid penetration resistance or impermeability of the material, restricting thus the dry heat flux by conduction, convection, and radiation, as convection and conduction transfer of heat caused by sweat evaporation and condensation. This paper deals with the study of the impact of clothing as baseline clothing, made from different functional materials, on thermoregulatory responses of human body in the limited heat and moisture transfer context. The results of the investigation show that the effect of baseline clothing, as an interface layer, worn under impermeable protective clothing, on thermoregulatory responses of human body, is limited during wearing in a hot environment.

Keywords: Clothing; Clothing Material; Cooling Effect; Thermoregulatory Response; Heat and Moisture Transfer

1 Introduction

The effects of clothing on thermoregulatory responses of human body have been studied by many researchers. Several reports show that heat transfer through clothing is significantly affected by human body and four climatic parameters: ambient air temperature, relative humidity, mean radiant temperature and air speed [1-6]. The clothing, designed on the basis of anthropometric requirements from two-dimensional textile surfaces, joined in a 3-D form, which covers the body as a shell [6], is not just passive cover for the skin; it interacts with and modifies the heat regulation function of the skin, and its effects are modified by the environment. Clothing, which mediates convective, as well as radiative and evaporative heat exchange, must be interpreted within the complete context of human physiological and psychological response. Therefore, the fact should not be neglect that the type, construction and structure of clothing, resp. clothing system worn can have an important impact on heat dissipation during different activities.

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In terms of thermophysiological comfort, which is characterized by three divergent processes (during normal wear, under transient wear conditions, and under specific wear condition), the behaviour of clothing in these three different domains may be treated as a complex system. Namely, clothing comfort is determined by a number of clothing properties that affect the thermal conditions of the skin. During normal wear, the human body continuously generates low amount of perspiration, meaning that human body produces some sweat or saturated water vapour, which must be progressively dissipated to maintain thermoregulation and a feeling of thermal comfort. The clothing becomes a part of the steady state thermoregulatory system [7]. Under transient wear conditions, characterized by heavy sweating caused by strenuous activity or climatic conditions, noticeable amount of perspiration and liquid sweat occur und must be rapidly managed by the clothing, resp. clothing system, in order to maintain thermal regulation [7]. Contrary to normal wear and transient wear conditions, under specific wear conditions, characterized by heavy sweating caused by impermeable protective clothing, the effect of clothing, as an interface between the skin and the environment, is passive, and health and safety are priorities to comfort.

2 Problem Formulation

Clothing, i.e. clothing system, which is a heat exchange layer between the body and its environment, plays an important part in the thermoregulation process. This means that clothing provides a microclimate between the body and external environment, and the microclimate is very important to the process of heat and vapour transfer from the skin to the external environment.

Clothing acts as a barrier for heat and vapour transfer between the skin and the environment. This barrier is formed both by the clothing materials themselves (from physical, structural and matter properties of the fabric to design and structure of the clothing assembly as a clothing system) and by the air they enclose as well as the still air that is bound to its outer surfaces [6]. The problem becomes more complex in the case of protective clothing, which is designed to provide protection against one or more hazards, and requires liquid penetration resistance or impermeability of the materials. The clothing interferes with the evaporation of sweat from the skin, increases skin temperature and core temperature, while reduction in cooling efficiency can also be observed.

2.1 The Influence of Clothing on Thermal Load

Heat transfer from human body, through the microclimate between the body and the clothing system and the clothing system itself, to the environment, is a complex process. Heat production and heat loss as heat exchange between human body and the environment are described by following equation of heat balance:

$$\mathrm{M} - \mathrm{P}_{\mathrm{ex}} = \pm\mathrm{Q}_{\mathrm{R}} \pm \mathrm{Q}_{\mathrm{K}} \pm \mathrm{Q}_{\mathrm{C}} - \mathrm{Q}_{\mathrm{res}} - \mathrm{Q}_{\mathrm{E}} \pm \mathrm{S}, \tag{1}$$

where, M is the energy created by metabolic processes; P_{ex} is mechanical (external) power, needed to perform activities; Q_{R} is heat absorbed (+) or released (−) from the skin through radiation; Q_{K} is heat absorbed (+) or released (−) from the skin through convection; Q_{C} is heat absorbed (+) or released (−) from the skin through conduction; $\mathrm{Q}_{\mathrm{res}}$ is heat released through respiration; Q_{E} is heat released through sweat evaporation, and S is the accumulation of (+) or loss (−) of heat in the body (for heat balance $\mathrm{S} = 0$).

Metabolic energy M is generated within the body, and almost completely converted into heat, while only a small part is used as kinetic energy to enable the body to do mechanical work. As human body releases around 10% of the heat generated through respiration, and the remaining 90% through skin surface and clothing, the heat exchange process of a clothed person and environment, can be expressed by the following [8]:

$$\mathrm{M} - \mathrm{P_{ex}} = \mathrm{Q_{res}} + \mathrm{Q_{sk}} = (\mathrm{Q_{C\text{-}res}} + \mathrm{Q_{E\text{-}res}}) + (\mathrm{Q_C} + \mathrm{Q_R} + \mathrm{Q_{E\text{-}sk}}), \tag{2}$$

and

$$\mathrm{Q_{E\text{-}sk}} = \mathrm{Q_{E\text{-}sw}} + \mathrm{Q_{E\text{-}dif}}, \tag{3}$$

where, $\mathrm{Q_{res}}$ is the total rate of heat loss through respiration; $\mathrm{Q_{sk}}$ is the total rate of heat loss from the skin through the clothing; $\mathrm{Q_{C\text{-}res}}$ is the rate of convective heat loss from respiration; $\mathrm{Q_{E\text{-}res}}$ is the rate of evaporative heat loss from respiration; $\mathrm{Q_C}$ is the rate of convective heat loss from the skin; $\mathrm{Q_R}$ is the rate of radiative heat loss from the skin; $\mathrm{Q_{E\text{-}sk}}$ is the rate of total evaporative heat loss from the skin; $\mathrm{Q_{E\text{-}sw}}$ is the rate of evaporative heat loss from the skin through sweating; $\mathrm{Q_{E\text{-}dif}}$ is the rate of evaporative heat loss from the skin through moisture diffusion.

If the change of thermal energy content of the body, or the so-called rate of heat storage $\Delta\mathrm{S}/\Delta\mathrm{t} = 0$, the body is in thermal equilibrium, while if $\Delta\mathrm{S}/\Delta\mathrm{t} \neq 0$, it means that thermal balance in the body has not been accomplished through heat exchange with the environment and the body reacts an increase in the heat or the drop in body temperature. From the view of a practical approach, this means that clothing system worn can have very important impact on thermal energy content of the body durig different activities, which restricts dry heat flux by conduction, convection, and radiation, as convection and conduction transfer of heat are caused by sweat evaporation and condensation.

Figure 1 illustrates how thermal energy is transferred from human body through the microclimate and the clothing system to the environment when skin temperature $\mathrm{T_s}$ is higher than the ambient temperature $\mathrm{T_a}(\mathrm{T_s} > \mathrm{T_a})$ [9]. Heat energy is conducted through the fabric incorporated into the clothing system by conduction, convection and radiation simultaneously.

Heat transfer from the skin through radiation can be described as follows [9]:

$$\mathrm{Q_R} = \sigma\varepsilon_s(\mathrm{T_s^4} - \mathrm{T_a^4}) - \sigma\varepsilon_{\mathrm{cl}}(\mathrm{T_8^4} - \mathrm{T_a^4}), \tag{4}$$

where σ is the Stefan-Boltzmann constant, ε_s and ε_cl are the emissivity of the skin and the clothing system, $\mathrm{T_s}$ is skin temperature and $\mathrm{T_a}$ is the ambient temperature.

Heat transfer by conduction/convection through the trapped air located between the internal surfaces of the clothing system and human skin, i.e. through the microclimate, can be described as a resistance to heat flow between the two surfaces. The heat transfer coefficient α_{gap} between the clothing system and the skin can be defined as a function of the size of the air gap and the temperature of the trapped air:

$$\alpha_{\mathrm{gap}} = \frac{\lambda_{\mathrm{air}}}{\delta_{\mathrm{gap}}} Nu, \tag{5}$$

where Nu is Nusselt number, λ_{air} is thermal conductivity of the air, and δ_{gap} is the size of the air gap. Heat transfer is

$$Q_\mathrm{a} = \alpha_{\mathrm{gap}}(\mathrm{T_s} - \mathrm{T_2}). \tag{6}$$

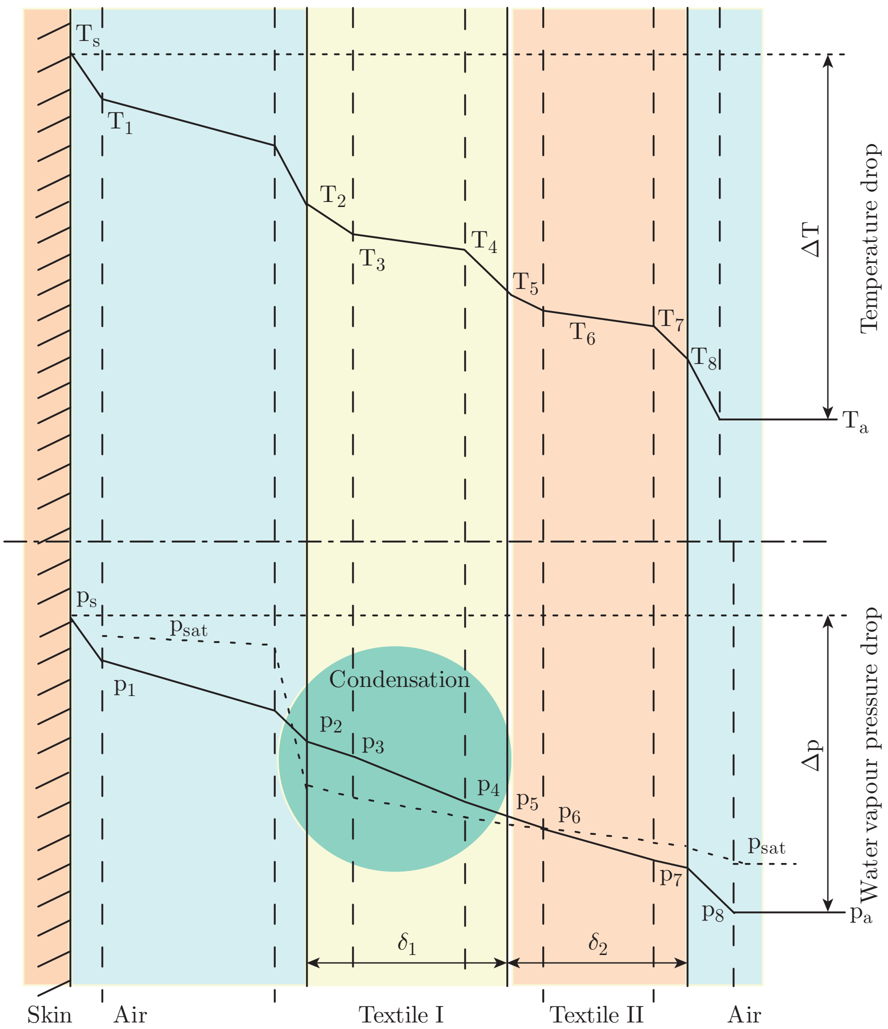

Fig. 1: Temperature and water vapour pressure during heat transfer

The conductive heat transfers through the clothing system, as a two-layered system, Fig. 1, can be determined as:

$$Q_{\text{cl}} = \frac{\lambda_{\text{avg}}}{\delta_1 + \delta_2}(\mathrm{T}_8 - \mathrm{T}_2), \tag{7}$$

where

$$\frac{1}{\lambda_{\text{avg}}} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}, \tag{8}$$

where λ_{avg} is the average value of the clothing system thermal conductivity; λ_1 and λ_2 are thermal conductivities of the clothing system's layers (Fig. 1).

Heat transfer from the clothing system to the environmental air can be expressed as:

$$Q_{\text{cl-a}} = \alpha_{\text{cl}}(\mathrm{T}_8 - \mathrm{T}_{\text{a}}), \tag{9}$$

where α_{cl} is the heat transfer coefficient from the clothing system surface to the ambient air.

At certain environmental temperature human body starts to secrete sweat, which evaporates on the skin surface and starts cooling the body. The evaporated sweat moves from the skin to the clothing system, where it partly condenses or moves through the clothing system, Fig. 1.

Evaporative heat loss from the skin can be obtained using the Asharae equation [10]:

$$E_{\mathrm{sk}} = \frac{w(\mathrm{p}_{\mathrm{sk,s}} - \mathrm{p}_{\mathrm{a}})}{\mathrm{R}_{\mathrm{e,cl}} + \dfrac{1}{\mathrm{f}_{\mathrm{cl}}\mathrm{h}_{\mathrm{e}}}}, \tag{10}$$

where, $\mathrm{p_a}$ is the water vapour pressure in the ambient air; $\mathrm{p_{sk,s}}$ is the water vapour pressure at the skin; $\mathrm{R_{e,cl}}$ is evaporative heat transfer resistance of the clothing layer; $\mathrm{h_e}$ is evaporative heat transfer coefficient; w is skin wittedness; $\mathrm{f_{cl}}$ is the clothing area factor.

Based on the Asharae equation for evaporative heat loss from the skin, it could be seen that clothing restricts evaporative heat loss, which is the main physiological mechanism for the body to lose heat in a hot environment. In the case of protective clothing, which is often impermeable and closed to protect against hazards, the evaporative heat loss through the clothing is disabled.

According to the above facts, the impact of clothing, as baseline clothing, made from different functional materials, on thermoregulatory responses of human body in the limited heat and moisture transfer context is presented in this paper.

3 Methodology

The effect of matter properties of clothing on thermoregulatory responses of human body in a hot environment was investigated. The investigation was performed for the baseline clothing, i.e. T-shirt, which was worn as the first layer under the impermeable protective clothing. The aim of this research was to establish the extent to which the baseline clothing worn under impermeable protective clothing provided thermal regulation to human body.

3.1 Materials and Test Methods

For the above purpose, the T-shirt as baseline clothing, made from different functional materials (high-tech functional fabric for active wear, and phase-change materials PCMs), Table 1, and impermeable coverall, were tested. The cotton T-shirt was chosen for comparison as it represented the garment most typically worn as the first layer under the impermeable protective clothing, and the Phase-Change Materials (PCMs) were used to test the effect of reducing the thermal stress and provided improved thermal comfort for wearers of protective clothing. Protective clothing was used the impermeable coverall made from microporous PE laminate.

3.2 Test Protocol

Tests of the effect of matter properties of baseline clothing on thermoregulatory responses of human body in a hot environment were conducted under artificially generated climatic conditions within a computer-controlled climatic chamber.

The test subject in each test performed the same physical activities according to the pre-defined protocol, Fig. 2, at the following environmental conditions:

- Ambient temperature: $\mathrm{T_a} = 32$ °C;

Table 1: Materials used for T-shirt

Designation	Fabric structure	Raw material content	Mass m ($g \cdot m^{-2}$)	Thickness h (mm)	Air permeability ($l \cdot m^{-2} \cdot s^{-1}$)	Warm/cool feeling q_{max} ($W \cdot m^{-2}$)	PCM storage capacity (J/g)
01-KFCo	Knitted fabric-Pique	100% Co	164.32	0.628	2260.6	0.133	-
02-KFCm	Knitted fabric double Piqué	57% PES Dacron Fresh 43% PES Dacron	168.38	0.895	2785.6	0.084	-
03-KFOu	Knitted fabric-Pique	38% Outlast PES 52% PES 10% spandex	150.60	0.650	1702.0	0.090	> 2.5
04-NFCl	Two layer non-woven	First layer: 100% PES Second layer: coating acrylate with PCM	255.66	0,477	1037.0	0,141	> 55

- Relative air humidity: RH = 85%;
- Air flow velocity: $v_a = 0.5\ ms^{-1}$;
- Radiation temperature equal to the ambient temperature $T_R = T_a$.

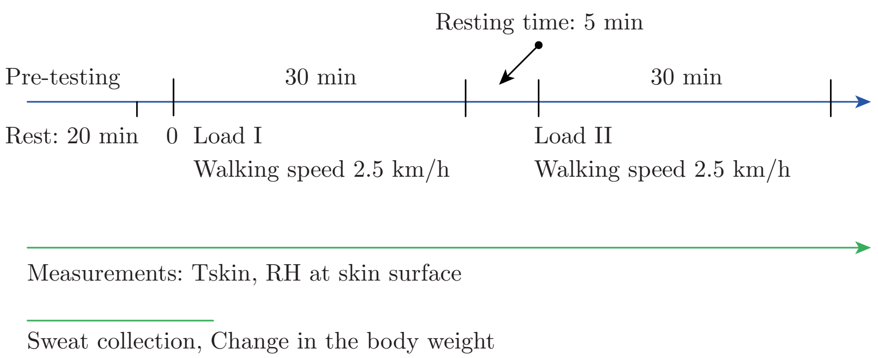

Fig. 2: Testing exercise protocol and measurement procedure

Walking was carried out on a treadmill workstation Jaeger LE 200, which was installed in the climate chamber.

Examination of physiological parameters as the thermoregulatory responses of human body in a hot environment was carried out using the Modular Signal Recorder MSR 12, company MSR Electronics GmbH. MSR 12 is a modular unit for measuring, displaying and recording various physical measurement parameters, such as skin temperature, and humidity at the skin surface (microclimate humidity), and heart rate.

The skin temperature and relative humidity at the skin surface of five different locations of the body, namely forehead, right scapula (back), left upper chest, left paravertebral, and right abdomen, were objectively measured according to EN ISO 9886 [11].

4 Results and Discussion

The results obtained indicate that the T-shirt as baseline clothing, made from selected knitted fabrics exhibited a considerable impact on thermoregulatory responses of human body in a hot environment. The analysis of the results showed that at the initial stage, i.e. during the first five minutes, when the testing subjects started performing activities at predetermined environmental conditions in a hot environment (T_a = 32 °C; RH = 85%), body response was at its highest. Considerable increase of skin temperature was recorded with testing subjects when wearing T-shirts designated 01-KFCo, rising for around 3 °C during the first 5 minutes (at the areas of right scapula, upper chest and left arm, for example), Fig. 3(a). Body reacted to the heat load created by sweating, which resulted in an incremental increase in relative humidity at the skin surface, Fig. 3(b). The secreted sweat, which evaporated on the skin surface, started cooling the body, and this resulted in the lag of skin temperature increase. After 20 minutes of activity (walk at the speed of 2.5 km/h), skin temperature started to decrease, which could be partly attributed to the effect of ventilation in the walk and partly to the evaporation cooling. When at rest, skin temperature slightly increases, while the second phase exhibits considerable fluctuations in temperature. Skin temperature drops at first due to ventilation, and then it grows again (up to the value of 36.25 °C). Skin humidity also increases, as relative humidity of the skin oscillates between 95 in 98% (the highest value of 98.95% was recorded in paravertebral area), Fig. 3(b).

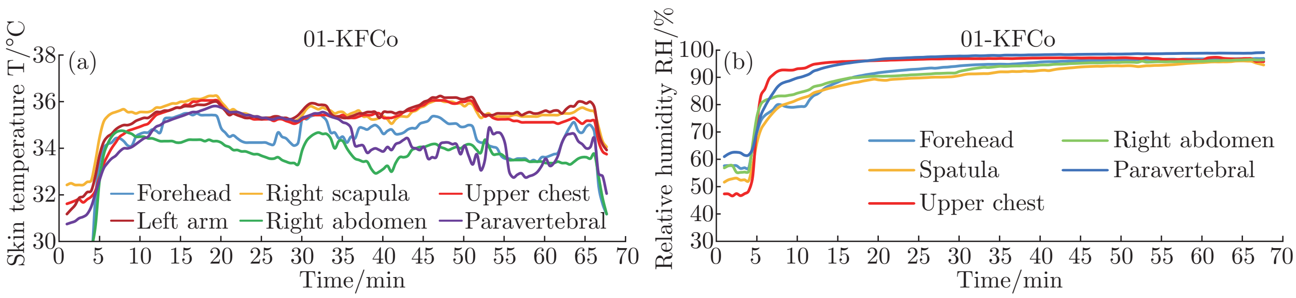

Fig. 3: Distribution of (a) skin temperature and (b) humidity at the skin surface in different parts of the body of the tested subjects while wearing t-shirt, made from the knitted fabric with the designation 01-KFCo

As opposed to the above, rather noticeable skin temperature increase occurred when testing subjects wore T-shirts designated 02-KFCm (rising for the first 5 min for about 2.5 °C), reaching the highest value in 20 min (between 35 and 35.5 °C; in the area of right scapula in the upper chest), after which skin temperature dropped, Fig. 4(a).

The reaction of the body to the rising skin temperature was reflected in faster increase in relative humidity at skin surface, which reached the value between 85% and 93% during the first 10 minutes, Fig. 4(b). Lower values of skin temperature for the tested subjects wearing the T-shirts designated 02-KFCm, as compared with the cotton T-shirt, could be attributed to its performance (effective respiratory system, and moisture transfer) and to the effect of ventilation in the walking exercise. Skin temperature rose again in rest, as ventilation and the ability to transfer humidity i.e. evaporated sweat, was reduced. At the start of the second loading phase skin temperature was slightly lowered, to be followed by reappearance of the rise tendency. However, it was lower than 36 °C throughout the phase (the highest value recorded was 35.75 °C; in the area of the scapula), Fig. 4(a). Relative humidity at skin surface was not significantly changed, and reached the value of 98.6% in the abdomen area Fig. 4(b).

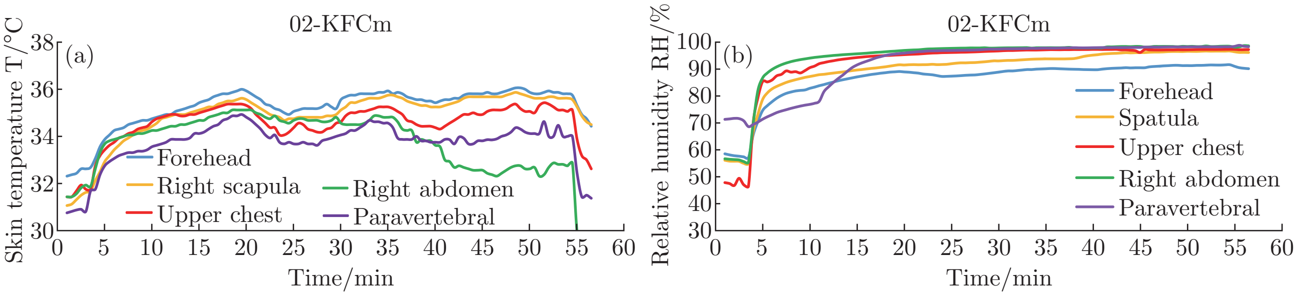

Fig. 4: Distribution of (a) skin temperature and (b) humidity at the skin surface at different parts of the body of the tested subjects while wearing t-shirt, made from the knitted fabric with designation 02-KFCm

Considerable increase in skin temperature of the tested subjects was recorded also when wearing the T-shirt designated 03-KFOu. It rose by about 3° in the first 5 min, after which the increase was more moderate. Skin temperature stabilised after 15 minutes. Slight decrease in skin temperature was recorded, Fig. 5(a), with the increase in relative humidity at skin surface, Fig. 5(b). Slower rate of skin temperature rise could be attributed to the cooling effect of the Phase Change Material (PCM), which accumulated a part of body heat with the simultaneous cooling effect of the evaporated sweat on the skin. Analysis of the results indicated that relative humidity at the skin surface reached relatively high values, ranging from 96% to 99.4%, Fig. 5(b).

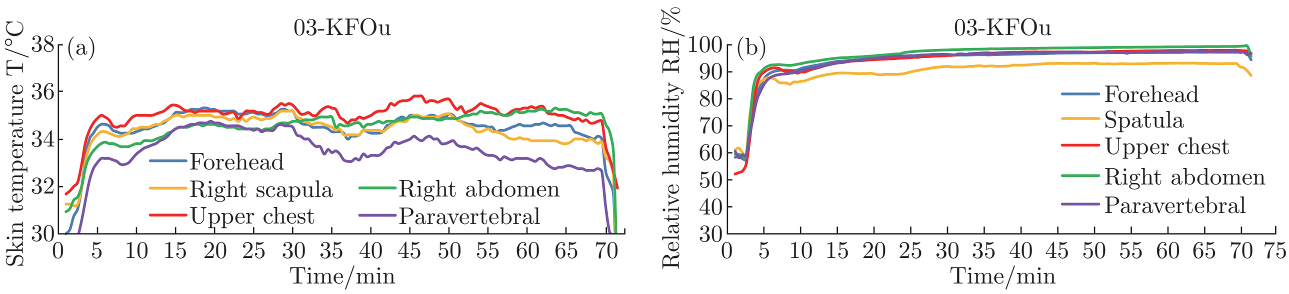

Fig. 5: Distribution of (a) skin temperature and (b) humidity at the skin surface in different parts of the body of the tested subjects while wearing t-shirt made from the knitted fabric with the designation 03-KFOu

Interesting facts were also revealed by the results of skin temperature analysis of the tested subjects when wearing the T-shirt designated 04-KFOCl, manufactured from the combined knitted fabric designated 03-KFOu (PCM storage capacity $\geq$ 2.5 J/g) and double-layer nonwoven designated 04-NFCL (PCM storage capacity $\geq$ 55 J/g) in the back and breast area. The results obtained indicated that skin temperature reached the value of 35.5 °C after 15 min, after which skin temperature oscillated in the interval of 15 min, Fig. 6(a).

Considerable high rate of the increase of relative skin humidity was recorded, reaching around 90% during the first 8 min, to approach the value of 99% after 40 min (the value of 99.56% relative humidity was recorded in the abdomen area), Fig. 6(b). Although selected phase change materials, designated 04-NFCL, exhibited high storage capacity (PCM storage capacity $\geq$ 55 J/g) and offered cool feeling (q_{max} equals 0.141 Wm^{-2}), it did not ensure the expected thermal physiological comfort in a hot environment. Despite high values of heat storage capacity, body reaction in a hot environment was negative, which can be seen from the distribution of relative humidity at the skin surface. It can be explained by relatively low value of air permeability, which restricted

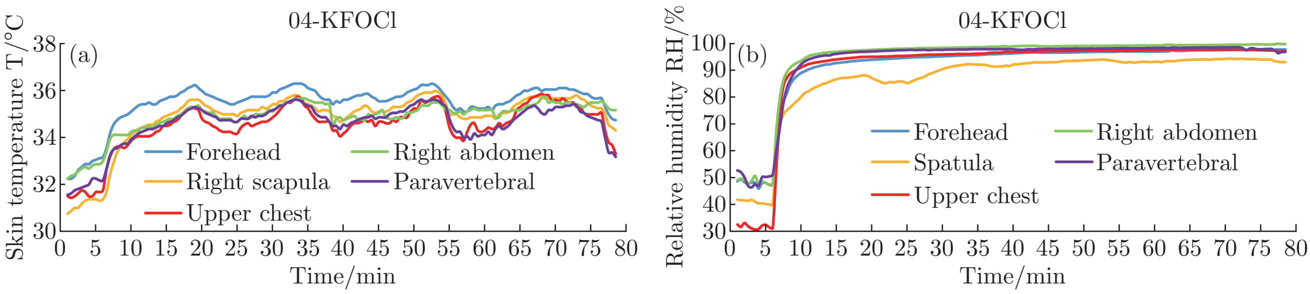

Fig. 6: Distribution of (a) skin temperature and (b) humidity at the skin surface in different parts of the body of the tested subjects while wearing t-shirt, made from the combination of knitted fabric with the designation 03-KFOu and nonwoven fabric with the designation 04-NFCL

the process of thermoregulation and retarded sweat evaporation, diminishing thus the effect of PCM storage capacity.

Based on the analysis of the results obtained, the second part of the investigation included studying the impact of three analysed T-shirts, as basic clothing, worn under the impermeable protection clothing. Analysis showed that considerable increase in skin temperature occurred in all the three cases, Fig. 7 to Fig. 9. The amount of secreted sweat also rose considerably, and the loss of body mass for around 1200 g was recorded. It should be noted that in the first case (i.e. wearing T-shirts without a protective clothing), tested subjects evaluated the feeling of heat as hardly acceptable, in the above case as "more unacceptable than acceptable". The analysis of the results for skin temperature changes in tested subjects, when wearing the T-shirt designated 01-KFCo, under impermeable protective clothing, showed that skin temperature rose

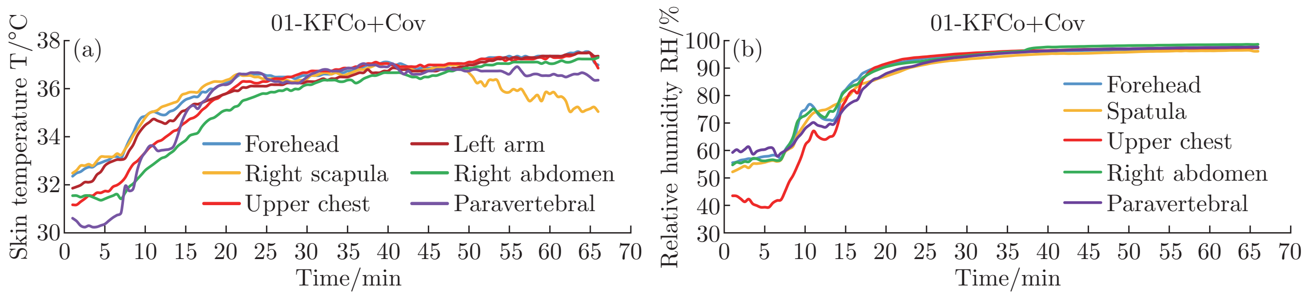

Fig. 7: Distribution of (a) skin temperature and (b) humidity at the skin surface at different parts of the body of the tested subjects, while wearing t-shirt made from knitted fabric designated 01-KFCo, under an impermeable coverall

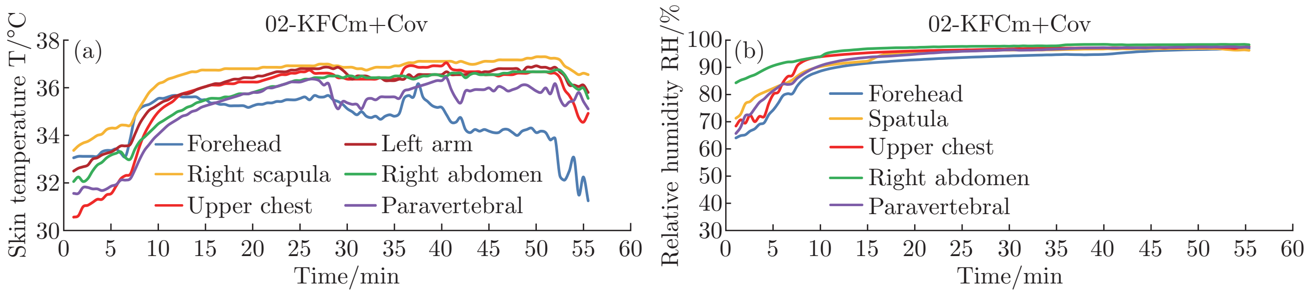

Fig. 8: Distribution of (a) skin temperature and (b) humidity at the skin surface at different parts of the body of the tested subjects while wearing the t-shirt, made from knitted fabric designated 02-KFCm, under an impermeable coverall

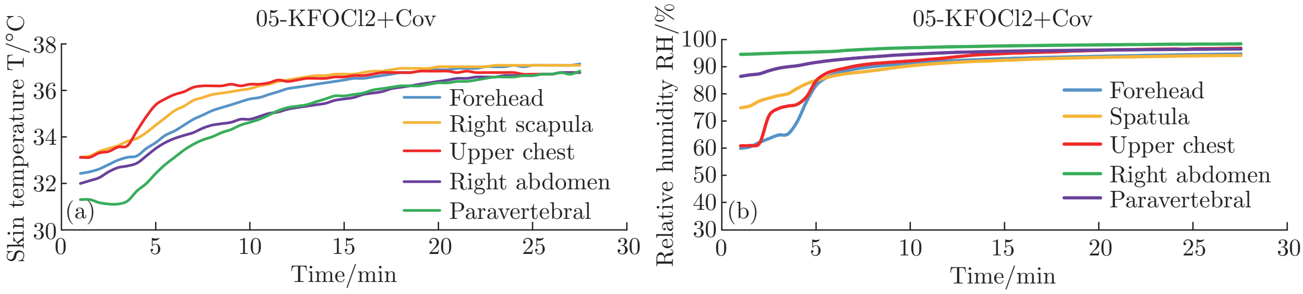

Fig. 9: Distribution of (a) skin temperature and (b) humidity at the skin surface in different parts of the body of the tested subjects while wearing the T-shirt designated 05-KFOCl, under an impermeable coverall

almost linearly for the first 20 min, skin temperature rising for around 5 °C and reaching the value between 35.2 and 36.4 °C, Fig. 7(a). Similar trend can also be seen in the distribution of skin humidity, whiche reached the values from 87 to 91%, Fig. 7(b). The lag in skin temperature increase at the initial part is due to evaporation enthalpy of the sweat and the associated skin cooling effect, as well as to the sorption properties of the analysed T-shirt as an interlayer. As heat and sweat transfer through the impermeable protective clothing was limited, the amount of water vapour in the microclimate area increased, to be condensed when it reached the saturation level. Heat is released in the process and the temperature of the microclimate further increased, which could be seen in higher values of skin temperature (up to 37.43 °C), while local temperature differences among various body areas were reduced. Relative humidity at skin surface increased as well, the skin becomes increasingly wet and the differences between the monitored areas were minimal (from 96.2 to 98.58%), Fig. 7(b).

Adequate trend was also recorded in the case of wearing the T-shirt designated 02-KFCm under the impermeable protective clothing. Distribution of skin temperature and humidity at the skin surface at different parts of the body of the tested subjects, while wearing the analysed t-shirt, is shown in Fig. 8.

At the initial stage, i.e. for the first seven minutes, skin temperature rose more slowly, and then it was rising at a faster rate and reached the value around 36 °C in 10 min, while in 15 min it rose to 36.75 °C. Relative humidity at the skin surface also rose at a faster rate, with the differences among the monitored body parts significantly narrowing. This intensive growth of skin temperature could be attributed to lower ability of water absorption of the T-shirt, as an intermediate layer, which reduced the cooling effect. Skin temperature was considerably reduced at rest, to be again increased in the second phase (the highest skin temperature recorded was 37.31 °C; in the area of the scapula), relative humidity at skin surface was 98.28%, which reflected considerable unpleasant microclimate conditions. Tested subjects confirmed this conclusion and evaluated the thermal state as “more unacceptable than acceptable”.

An interesting skin temperature distribution was recorded when wearing the T-shirt manufactured from the combined knitted fabric, designated 03-KFOu and double-layer nonwoven, designated 04-NFCL. Although the phase change material incorporated had a cooling effect, this effect was not realised, due to the limited heat transfer through the impermeable protective clothing. Skin temperature rose slowly in the initial phase (first 3 min), after which the increase was much more pronounced, Fig. 9(a), to reach 37 °C after 20 min. The differences in skin temperature values were reduced at this point, which indicated the loss of the cooling effect of the PCMs material.

Due to low sorption properties of the material, the effect of evaporative cooling was also considerably lower, which resulted in higher thermal load on the tested subjects. This was confirmed by the fast growth rate of relative humidity of the skin, as well as significantly reduced difference in skin humidity at different parts of the body monitored, Fig. 9(b). The experiment was stopped because of unpleasant thermal loads the subjects experienced.

5 Conclusion

The results of the investigation shows that the effect of baseline clothing, as an interface layer, worn under impermeable protective clothing on thermoregulatory responses of human body is limited during wearing in a hot environment. Namely, in exercising or working in a hot environment, the dry heat flux by conduction, convection, and radiation cannot match the metabolic heat production. Appreciable sweating starts to create a latent heat flux by evaporating sweat at the skin surface. Increased sweat evaporation increases the relative humdity of the microclimate with which the clothing is in contact, which leads to discomfort, if adequate vapour transmission is not permitted by the clothing.

Although different high-performance materials are aimed, through their functional performances (active wear and/or PCMs), reach thermal balance of human body in a hot environment, their functionality is limited and the effects are of different nature. Results obtained in the investigation show different human body thermoregulatory responses when wearing the analysed T-shirts in a hot environment. Apart from the sweat secreted, which evaporates at the skin surface, various effect are recorded (e.g. evaporative cooling is pronounced when wearing the cotton T-shirt, due to the evaporation of the accumulated sweat; the effect of cooling when wearing the T-shirt designated 02-FKCm can be attributed to humidity transfer, while a short-lived effect of the PCMs is recorded when wearing the T-shirt designated 03-FKOu in 04-NFCL, the material accumulating a part of the body heat).

The thermoregulatory response of human body was considerably different when wearing the analysed T-shirts as a baseline clothing, under impermeable protective clothing. Namely, the impermeable protective clothing blocks air and water vapour transport, and evaporative heat loss through such material is impossible, the result being that water vapour is accumulated in the microclimate until saturation is reached and the first drop of liquid water is formed (exothermic process). This leads to the release of heat (enthalpy changes of condensation are negative), and the temperature of the microclimate further increased, which results in a complex thermodynamic process in the area of the microclimate. This is directly reflected in both in the skin temperature and core temperature increase, and leads to heat stress.

The analysis of the results on thermoregulatory responses of human body during wearing analysed baseline clothing under impermeable protective clothing show that, despite the use of contemporary high-performance materials, it is not possible for now to provide adequate comfort in a hot environment without exposing human body to a heat stress.

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