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The Role of the Textile Layer in the Garment Package in Suppressing Transient Heat Exchange Processes

Abstract
An exchange of various forms of energy between a human and the media surrounding him proceeds continually, and the process preserves this continuous dynamic balance during his life. Thermal energy exchanges occur mainly through the clothes which a human wears. Thus, the package of clothes participates in energy exchanges between man and his media reducing the dynamics of heat transfer. When seeking to ensure thermal comfort to a wearer, it is necessary to assess the ability of the garment's design as well as its material to reduce dynamic thermal energy processes. The investigation presented herein by us, was carried out having mainly in mind its application for designing working clothing. In reality our conditions and conclusions are concerned with a significant broader range of garments. We carried out investigations aimed at evaluating the role of thermal insulation properties of garment materials and clothes in lowering the external thermal energy dynamic processes. Data on temperature fields in working garments as influenced by the outer average temperature are presented. It was found that at a certain depth , the heat exchange processes become steadier. This depth indicates the optimal thickness of the clothes package. The optimal layer thickness allows us to determine the garment's thermal resistance which can be recommended with the evaluation of transient conditions and the temperature variation dynamics of the surrounding air.

Key words: *clothes package, temperature field, thermal energy processes.*

Introduction

The investigation presented herein by us, was carried out having mainly in mind its application for designing working clothing, which is a very important, and at the same time difficult problem, considering the changing use-conditions. Therefore, we use qualifications as 'working garment', 'protect a worker', 'worker's thermal comfort', etc. In reality our conditions and conclusions are concerned with a significant broader range of garments.

For a worker in an environment with periodically changing temperature, transient short-duration processes take place. The problem arises of how to protect a worker from the thermal effect of changing temperature and from thermal stress during any sudden change of physical work. The issue of reducing the worker's thermal regulation tension is dealt with by considering his thermal balance, comfort models of work conditions, thermal stress, the worker's temperature topography, the garment's heat resistance and other garment design problems [1-11]. A deeper analysis is needed of the processes which take place in the garment itself, between the human body and work garment in transient cases.

The worker's thermal condition is usually regulated by choosing clothes with suitable thermal insulation properties [12]. Currently thermal resistances of clothes are established for steady heat transfer conditions, according to standards ISO 9920:1995 [9] and ISO 7730:1994 [10]. Such determining of thermal resistance for steady heat exchange fails to match real processes and the results of experimental research. Therefore, reduced values of garment thermal resistance and their corresponding correction factors were proposed [5-7]. Standard ISO/TR 11079 [11] based on the heat exchange model by L. Holmer, recommends establishing the necessary garment thermal resistance IREQ, which in all cases of physical loads is smaller than that found using the usual methods [5]. Thermal resistance of a garment is also found by assuming the stationary process of heat exchange, as the IREQ methodology neglects the dynamics of thermal energy processes.

Temperature variation dynamics in the surrounding air during physical activities and additional heat generated by the human body itself can cause thermal stress conditions. Working clothes have a direct influence on a worker's thermal and comfort condition during his work. Many authors have raised the question of proper analysis of thermal stress during work [5-8]. In such a situation, determining optimal thermal resistance, the choice of garment design and material parameters become problematical.

The dynamics of thermal energy processes of the system environmental air-work clothes- man are directly dependent on periodic temperature changes of the surrounding air in the workplace, and predetermine heat distribution in a working garment with certain thermal insulation properties. The objective of matching working clothes to real work conditions with evaluation of the average temperature changes cannot be pursued by considering the steady-state regime alone. It is necessary to search for methods of evaluating temperature field variation dynamics in a garment layer in a medium of varying temperature.

The objective of this research is to investigate theoretically and experimentally the effect of varying the temperature of the surrounding medium upon temperature fields in the garment, and on the basis of the dynamics of temperature fields in a textile layer of the garment, to assess its ability to suppress temperature changes caused by outside temperature variation. With these results, we will determine the recommendable thickness of the garment. The environment with changing temperature, unsteady conditions and temperature dynamics must be taken into account.

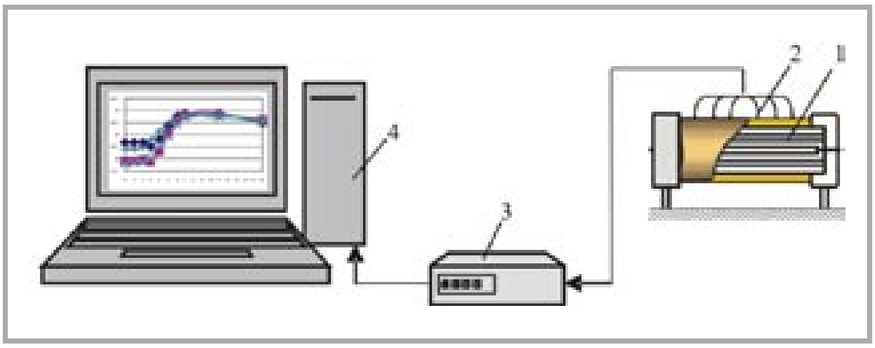

***Figure 1**. Principle scheme of the temperature measurement device (conductivity meter): 1 – object investigated; 2- temperature sensors; 3- ALMEMO 2590-9 measurement data accumulating device; 4- computer.*

Work objective and methodology

To solve the problem of evaluating a temperature regime in the garment, experimental work and mathematical modelling of the temperature field in the garment was carried out. The environmental temperature field penetration into the garment was investigated in woven cotton, half-wool, wool and nonwoven cotton and half-wool fabrics with thermal conductivities λ of 0,0582…0,069 W/(m·K), material density ρ of 13…50 kg/m^3, and heat capacity c of 1340…1750 J/(kg·K).

A thermal conductivity measurement device was used for experiments [13]. The basic scheme of this device is presented in Figure 1.

The temperature measurements were carried out using individually manufactured Cu-CuNi thermocouples with wires of 0.07 mm in diameter. While measuring the temperatures of the material's outer and separate layers, the sensors were attached along the isotherm on a length equal to 100 sensor diameters. The temperatures were registered using an ALMEMO 2590-9 device with microprocessor data processing and accumulation systems. From the ALMEMO 2590-9 data accumulation system data was sent to the computer for further data processing. The resolving power of the device is 0.1°C. The relative uncertainty of the temperature estimation is 0.07% for 99% reliable probability.

In the first phase of investigating the influence exerted by the environmental temperature changes on temperature fields in garment material, a steady-state temperature regime was obtained. In the second phase of investigations, the surrounding environment temperature was varied (Δt_{env}=15 °C), and this periodically influenced garment temperature field. The cooling period lasted 30 min.

Mathematical modelling was carried out applying the PLAFI code [14], which uses the finite difference method. The garment cross-section plane was covered with a rectangular grid, with every node point having an elementary cell assigned to it. According to the finite difference procedure, a heat balance equation was obtained for every cell. The calculation procedure included iteration in every cell node until the temperature change obtained was not greater than 0.0001 °C. Mathematical modelling was carried out for the same thickness of material, for the same external conditions and with the same thermal properties as registered in experiments. Mathematical modelling was additionally applied for materials of different thickness and temperature changes in an environment reaching Δt_{env}=10 °C and Δt_{env}=20 °C. The thermal exposure duration was 60 min.

Results of investigation

Theoretical substantiation

For a worker entering an environment with periodically changing temperature, the transient short processes above mentioned take place. Dynamic heat exchange processes manifest themselves which are typical of an unsteady temperature regime. During an unsteady regime, a sharp environmental temperature leap Δt_{env} disturbs the temperature equilibrium of the system environment air-work clothes-man and the heat transfer through the garment (Figure 2). This gives rise to temperature changes on the outer garment surface $t_{out}\pm\Delta t_{env}$ and within the garment $t_g(x,\tau)$. During a steady temperature regime, without dynamic heat exchange processes (Figure 2, section AB), the flow density of heat transfer through the garment is constant (q_h=const), and in the garment layer δ the temperature depends linearly on the garment layer thickness x_i at a certain moment of time.

In real conditions, the surface temperature of the inner surface t_{in} of the garment worn by a worker is maintained by a constant flow of heat out of the human body (this assumption of ours is valid for the investigation presented; the influence of physiological aspects, e.g. physical activity or the heaviness of work will be the subject of further investigations). In this case (Figure 2) we have a constant heat flow density q_h=const from the inside of the garment. However, under the influence of the environmental temperature, heat flow from the outer surface of the garment is already transient and has an additional component $\pm\Delta q_{env}$, so the flow is equal to $q_h\pm\Delta q_{env}$. Thus, in the garment layer two temperature fields meet, and in their intersection zone an imaginary stable point X exists.

Depending on the environment temperature change $\pm\Delta t_{env}$, its effect duration τ and garment material conductivity λ, the point X moves along an imaginary section from A to B. The position of this imaginary stable point directly describes the optimal thermal insulation layer thickness δ for a concrete environmental temperature effect and the duration of work in the changed surrounding air temperature.

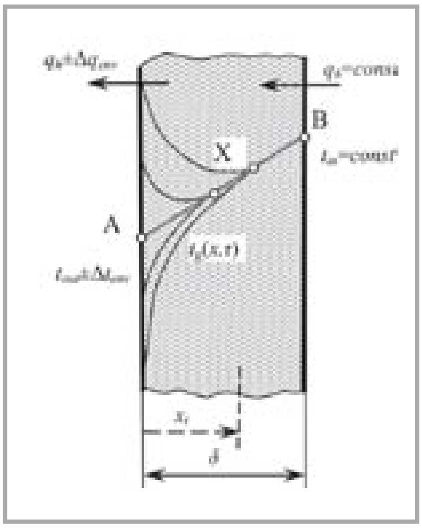

***Figure 2.** Influence of varying thermal environment temperature on temperature field in the garment layer. Explanations in the text.*

While considering the role of cloth tissues in suppressing the external dynamic heat exchange processes, the heat diffusion equation [15] must be solved as the basis for our description of the one-dimensional temperature field in the work garment:

$$\frac{\partial t_g}{\partial \tau} = a\left(\frac{\partial^2 t_g}{\partial x^2}\right) = \frac{\lambda}{c\rho}\left(\frac{\partial^2 t_g}{\partial x^2}\right), \qquad (1)$$

where:

t_g - temperature in the garment, °C;

τ - time, s;

a - temperature diffusivity, m^2/s;

λ - thermal conductivity, W/(m·K);

c - specific heat, J/(kg·K);

ρ - density of material, kg/m^3.

The complexity of the influence exerted by the outer thermal energy processes on the dynamics of internal temperature fields in the garment decisively affects the choice of boundary and initial conditions for solving this equation. We established boundary conditions for solving the equation (1) regarding the garment material layer as a one-layered plane plate, through which heat is transferred from the human body to the surrounding air. In such a case the initial condition is expressed by the following equation:

$$t_g(x,0) = t_{int} = f(x_i), \qquad (2)$$

where:

$t_g(x,0)$ - initial temperature at point $(x,0)$, °C;

t_{int} - initial temperature in the garment, °C. This may be determined from stationary regime regularities or concrete results of mathematical modelling;

$f(x_i)$ - functional dependence of temperature upon thickness of garment layer x_i (expressed by a linear or other equation);

x_i - garment thickness, mm.

It follows from the initial condition (2) that at the initial moment of time (τ=0) on the garment's outer surface and at any thickness x_i the temperature depends on the function $f(x_i)$.

On the contact of the garment's external surface with the surrounding medium point, when $\tau \neq 0$, we have the first boundary condition described by the equation:

$$\frac{\partial t_g(0,\tau)}{\partial x} = -\frac{\alpha}{\lambda}\left[t_{env} - t_g(0,\tau)\right], \qquad (3)$$

where:

α - heat transfer factor, $W/(m^2 \cdot K)$;

t_{env} - thermal environment temperature, °C.

The second boundary condition, where the heat flow from the human body surface is constant (Figure 2), may be written thus:

$$t(\delta,\tau) = t_{int} = f(x_i), \text{ when } q_h = \text{const}, \qquad (4)$$

where:

$t(\delta,\tau)$ - temperature at thickness of the garment material δ, °C.

δ - total thickness of garment layer, mm.

We have chosen the case for investigation when the temperature of the thermal environment is 10 °C and the temperature of the garment's inner surface is 23.59 °C. As the initial distribution of temperature we described a dependence of the initial temperature t_{int} on the thickness of the garment material thus:

$$t_{int} = 0.859\delta + 15. \qquad (5)$$

While modelling the temperature field in the garment layer, we found the temperature t_g for any moment of time τ at garment layer thickness x_i; that is, we tried to define the following part of Equation (1):

$$\frac{\partial^2 t_g}{\partial x^2} = \frac{\partial t_g}{\partial \tau}\frac{c\rho}{\lambda}. \qquad (6)$$

The differential equation (1) was solved using the finite differences method and the initial (5) and boundary conditions (3), (4). A numerical simulation of temperature fields in garment materials with different properties and thickness elucidates the role of garment material tissues in reducing the influence of dynamic external thermal energy processes.

Results of experimental investigations

Experimental investigations of temperature fields in the garment were carried out using a device for textile material thermal conductivity measurements according to the methodology above mentioned.

After reaching a steady temperature regime, that is, with temperature equilibrium achieved in the layers of the material investigated, the influence of the thermal environment's temperature dynamics on the ability of textile materials to suppress outer temperature changes was studied. As one representative example, we present the results of an experimental investigation carried out with wool fabric (linear density of yarns 110 tex, set in warp and weft 170 dm^{-1}, twill 2/2), with a thermal conductivity λ=0,062 W/(m·K), density ρ = 50 kg/mł, specific heat c = 1340 J/(kg·K), layer thickness 0.8 mm; the thickness of a package containing 10 such layers is 8 mm. Temperature measurements were carried out using thermocouples placed in every second material layer. With the temperature lowered by Δt_{env}=15 °C, a slow temperature drop was observed in separate small material package layers (Figure 3).

For a more detailed study of the depth of penetration by the environment temperature into the garment's material layer, and of the ability of the thermal insulation properties to suppress dynamic processes of heat exchange with a dynamic environment, comparison was made of the experimental results and the results of the mathematical modelling.

Results of mathematical modelling

The mathematical modelling of the temperature field in the garment material under the influence of a thermal environment was based on the results of experimental investigations. The same

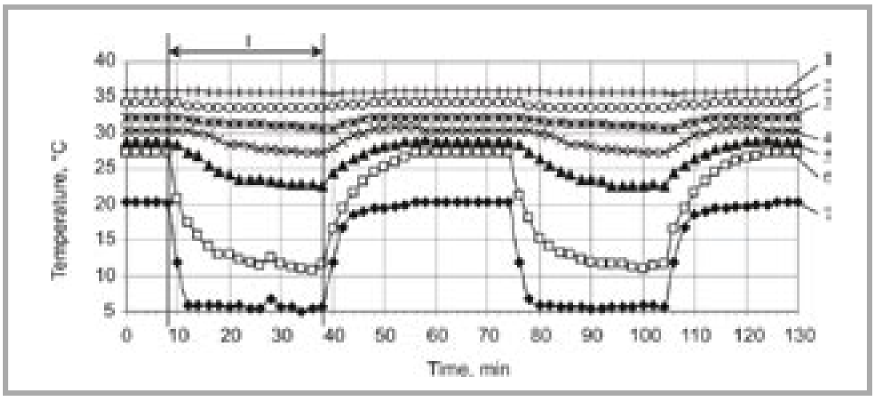

Figure 3. Effect of environment temperature in wool material with λ=0.062 W/(m·K), ρ=50 kg/mł, c=1340 J/(kg·K). Temperatures: 1 – on the inner surface of material; 2, 3, 4, 5 – in layers having thickness 1.6; 3.2; 4.8; 6.4 mm correspondingly, 6 – on the outer surface of material; 7 – of environment; I – cooling period.

ambient temperature values and material cooling time intervals as those obtained experimentally were used as the initial and boundary conditions in the modelling process. The numerical simulation of temperature field in garment material was carried out every other 10 min at every cooling period I (Figure 3), using experimentally obtained temperature values in each layer of the material package in a steady-state temperature regime. With mathematical modelling using the PLAFI code of the temperature field in garment material under the influence of the thermal environment having been carried out, we plotted the results taken from experiments together with the numerical simulation results (Figure 4). It can be seen from Figure 4 that the results of the experimental investigations and mathematical modelling are very close. Small discrepancies between experimental investigations and theoretical values can be noted in the case of the data from the layer 1 to 3 mm thick when the environment temperature influenced it for 10 to 20 minutes, as well as in the case of the data of the layer 1.6 to 6 mm thick, when the environment temperature was raised for 30 minutes. The discrepancies between the experimental and theoretical data are small, not exceeding 1 °C, or 4%.

We compared the numerical simulation and experimental research results for some moments of time by calculating the correlation coefficients. We found that a strong correlation bond exists between the temperatures obtained empirically and numerically (the correlation coefficients are 0.97-0.99).

Investigating the role of the cloth layer of the garment package in suppressing transient heat exchange processes with environment analogous numerical simulation and experimental research results were obtained for other garment materials, which are described in the methodology part of this work.

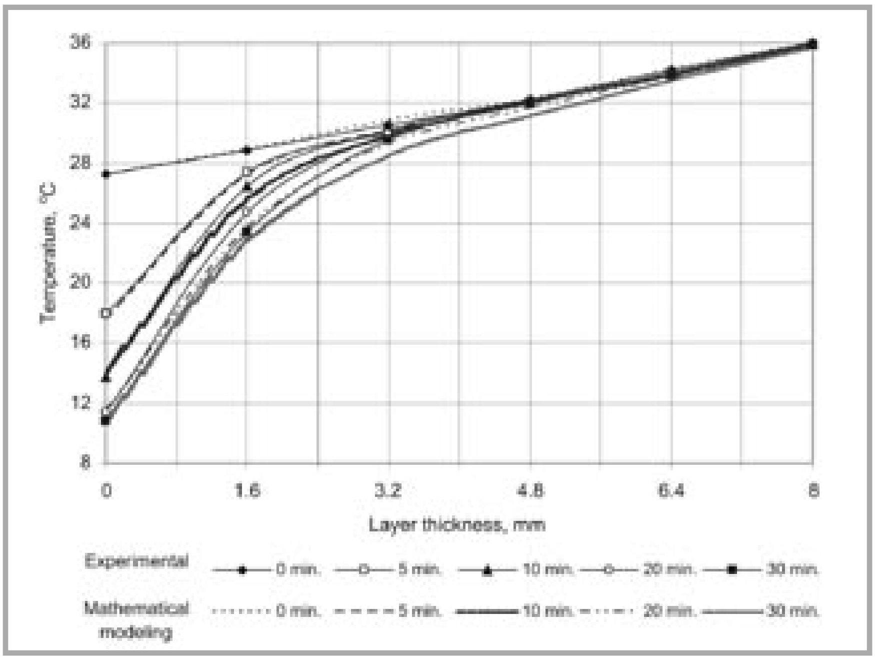

Figure 4. *Comparison of results of experimental investigation and numerical simulation. Materials investigated with $\lambda=0.062$ W/(m·K), $\rho=50$ kg/mł, c=1340 J/(kg·K), package thickness 8 mm.*

Conclusions

1. The cloth layer diminishes dynamic unsteady heat exchanges with the thermal environment.

2. Transient temperature fields suppressed in the garment layer asymptotically approach a steady state. Garment layer thickness reaching steady temperature describes the optimal (minimum) garment package thickness for the garment designed for a givgen purpose.

3. A mathematical modelling methodology may be applied to designing a garment package layer for a periodically varying thermal environment.

4. Determining garment thermal resistance according to standards ISO 9920:1995, ISO 7730:1994 and ISO/TR 11079 ignores the unsteady heat exchange processes taking place in textiles, and for that reason they are not applicable for designing clothes for work in conditions of unsteady heat exchanges with the thermal outer environment.

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