Grażyna Bartkowiak

Influence of Undergarment Structure on the Parameters of the Microclimate under Hermetic Protective Clothing

**Central Institute for Labour Protection
- National Research Institute,
Department of Personal Protective Equipment**
ul. Wierzbowa 48, 90-133 Łódź, Poland
e-mail: grbar@ciop.lodz.pl

Abstract
Work in conditions dangerous for the human being requires appropriate protective clothing. Working in hermetic protective clothing is connected with a considerable heat burden for the user's organism. The condition of the organism is influenced not only by the external protective clothing but also by the underwear worn directly on the body. On the basis of an analysis of hydrothermical conditions under hermetic protective clothing during physical activity, a model of two-layer fabric for undergarments, which should facilitate the elimination of sweat from the user's skin, has been developed. Tests of underwear made using a model fabric system consistent with the model developed were conducted on young men in a microclimatic chamber, the results of which were compared with traditional cotton underwear, showing that the microclimate under the hermetic protective clothing was more favourable in the case of the model system. The results of the tests indicate that it is possible to reduce discomfort associated with work in hermetic protective clothing by providing workers with appropriate undergarments actively involved in sweat elimination from the user's skin.

Key words: *hermetic protective clothing, undergarment, underwear, thermal comfort, under – clothing microclimate.*

Introduction

Work, especially in conditions harmful for the human being, requires the use of protective clothing. Its fundamental purpose is to protect the worker against hazardous factors present in the working environment. Protection against aggressive chemicals requires the use of impermeable garments coated with synthetic polymers that create a hermetic barrier between the human body and the hazardous environment. Working in hermetic protective clothing leads to considerable thermal stress experienced by the user and is associated with additional effort [1]. An extreme example of discomfort is the use of clothing providing protection against aggressive chemicals, so-called gas-tight clothing, the construction of which effectively prevents the exposure of the human body to harmful substances but, on the other hand, considerably impairs thermoregulation processes.

Advances in the textile industry, including the production of fabrics creating a barrier for dangerous agents, has led to considerable progress in the construction of protective clothing. Recently special attention has been paid to microfiber fabrics, flat textile, semi-permeable membrane laminates, microporous coating films, and multi-layer materials, some of which can be used in the construction of protective clothing, replacing hermetic materials.

Research carried out all over the world [2, 3] has shown that undergarments worn directly on the body may have a considerable impact on the thermal comfort of the user. An analysis of specialist literature indicated the lack of a complex approach to this problem, especially in the case of hermetic protective clothing. The correlation between the characteristics of undergarment materials worn under hermetic protective clothing and the dynamics of an undergarment microclimate, assessed both in a laboratory and working conditions, has so far not been analysed.

The aim of the present study was to assess the influence of an undergarment worn directly on the body upon the undergarment microclimate and comfort of a user requiring hermetic clothing protection against chemicals.

Thermal stress imposed on the human organism working in hermetic protective clothing

During physical activity, the energy produced by the human body is transformed into mechanical work only to a small extent 5 - 25%: the rest is mainly 75 - 95% utilised in generating heat, which imposes endogenous stress on the organism [4].

The worker can also acquire egzogenous heat from the environment. Maintaining a stable body temperature requires continuous heat exchange with the environment. Man and his environment constitute a system of communicating vessels in which heat flows. If the heat generation exceeds its expenditure by conduction, convection and radiation, the organism starts to produce sweat on the surface of the skin, which takes place mainly in an environment characterised by a hot microclimate or during intensive physical activity, particularly during work in tight, hermetic clothing. The quantity of sweat produced fully meets the organism's need for thermoregulation and depends on the external temperature, energy expenditure, garment type and the individual predispositions of the subject. Therefore, a prediction of sweating intensity based on the appropriate normograms is biased by a considerable error, giving only approximate values. The most common sweat quantities range from 0.5 to 3 l per working shift [5, 6]. However, in specific working conditions, sweat loss may be higher. Lehman [5] reports that situations in which sweat production reaches 0.8 l/h are frequent. Sweat plays a thermoregulatory role only if it can evaporate, which is impossible in hermetic protective clothing.

Hermetic protective clothing, enclosing a small space surrounding the body, has a specific influence on the microclimate close to the skin, making natural regulation favourable for the organism more difficult. Creating a barrier between the body and a hazardous working environment interferes with heat and water vapour exchange between the organism and its surroundings. The total amount of heat generated by the worker's organism cannot be transferred outside to the environment as it accumulates under the tight impermeable clothing, leading to an increase in body temperature and undergarment microclimate humidity up to a state of saturation. It is impossible for sweat secreted profusely under such conditions to evaporate. Consequently, sweat accumulates on the skin and on the inner surface of the garment, increasing user discomfort. Hermetic protective clothing creates an extremely unfavourable undergarment microclimate characterised by high relative humidity and air temperature, imposing stress on the user's organism and, especially, on his cardiovascular system during physical activity [7].

The marked impact of microclimate parameters and humidity, in particular, on user sensations associated with thermal comfort has been emphasised [8]. Under normal conditions, relative underwear humidity ranges from 40 to 60%, whereas values exceeding 70 - 80% and the rapid increase in humidity is connected with the sensation of steaming, dyspnoea and severe discomfort, additionally increased by the presence of liquid sweat on the skin. The parameters of a clothing microclimate associated with the amount of sweat are directly connected with the physical load, climatic conditions and the complex clothing system.

The Central Institute of Labour Protection has carried out a series of researches on the impact of protective clothing made of coated materials on the user's organism [9, 10]. The basic method used for the assessment of stress imposed on the organism by doing work in the protective clothing was the monitoring of cardiovascular system reactions, primarily measurements of the heart rate and arterial blood pressure [11]. The phenomena taking place in the subject-clothing-environment system were also illustrated using undergarment microclimate parameters.

Using hermetic protective clothing causes an increase in the energy expenditure associated with work. It was noted that wearing a garment made of coated fabrics increased the energy expenditure by an average value of 3.5 kJ/min, shifting the work classification from light and moderate to moderately hard. For the same activities performed in a gas-tight suit, the energy expenditure was 11 to 34% higher than that occurring during work in cotton overalls. Using coated protective clothing in an environment characterised by high temperature is especially burdensome for the organism of a human being. It was observed that even during low-intensity work, people wearing chemical-tight clothing made of coated materials in high temperatures require significantly shorter working times, as well as more frequent and longer breaks than the others. The microclimate under the hermetic protective clothing was characterised by a rapid increase in temperature and humidity, and a state of saturation was often reached after 20 min of the work load.

As follows from the studies, using hermetic protective clothing in the working environment requires scheduled breaks necessary for regeneration after work because of the considerable stress imposed on the user's organism. The organisation of work is dependent on climatic conditions in the working environment, the energy expenditure, the kind of protective clothing and on the worker's efficiency.

Model of fabric designed for underwear to be worn under hermetic protective clothing

Analysis of hydrothermal conditions under hermetic protective clothing and the impact of the textile fabrics used on the microclimate under the clothing was made to develop a model of a textile multilayer knitted fabric designed for underwear to be worn under tight protective clothing for work requiring intensive physical activity, which is consequently associated with the generation of a considerable amount of heat and sweat [12, 13].

Sweat occurring on the skin surface should evaporate or be kept away from it, therefore, because it is not possible to transfer it to the environment, it should be absorbed in the form of vapour or liquid by the underwear material. In order to eliminate the wet, unpleasant sensation resulting from the sorption of humidity, the knitted fabric layer of the underwear, being close to the skin, should be made of a materialcharacterised by minimum liquid sorption and should have a structure ensuring efficient capillary transport. Therefore, underwear knitted fabric of a two-layer structure was adopted. The first layer (conductive-diffusive) should enable the water vapour diffusion and capillary transport of liquid, whereas the second one (sorptive, hygroscopic) should keep the humidity in its structure.

The model proposed for underwear fabric was made of materials different in their affinities to humidity [14]. A model of a multilayer fabric used under hermetic clothing impermeable to water vapour is presented in ***Figure 1***; it consists of two layers, each of which has different properties and functions:

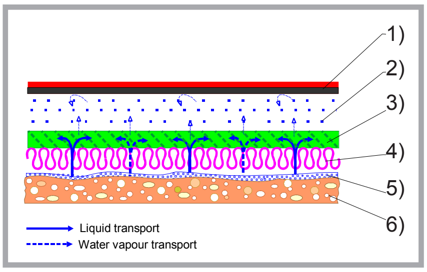

Figure 1. *Model of material under a hermetic water – steam –tight barrier [12]; 1) barrier, 2) water vapour, 3) sorptove layer, 4) conductive and diffusive layer, 5) sweat, 6) skin.*

- the first inner layer – knitted fabric made of hydrophobic fibres with an openwork structure – will enable the diffusion of water vapour and liquid transfer, remaining dry itself, or quasi-dry.
- the second, outer layer, characterised by a high sorption and high absorption capacity – may be made of knitted or nonwoven fabric of hydrophilic fibres, or another highly sorptive material with an appropriate mass per square meter, which will absorb liquid from the inner layer and is responsible for liquid transportation.

Characteristics of the clothing system with the undergarment used in the study

Tests were carried out on 2 types of undergarment in a microclimatic chamber, one of which was made of a fabric system consisting of the two-layer model proposed. The system of fabrics in the two-layer model was chosen after testing the sorption and dynamics of the underwear microclimate of many fabrics in laboratory conditions. Pique-type knitted fabric made from textured PES yarn for the first layer and pique-type knitted fabric made of viscose yarn were chosen, which were sewn together to obtain two-layer material. This kind of undergarment was used in variant A2 of the clothing tested.

A reference variant of the undergarment was made of interlock cotton knitted fabric of a similar surface mass as the two-layer material previously described. This kind of undergarment was used in variant A1 of the clothing tested.

The total surface mass of the two-layer system of fabrics (PES and viscose) – 316 g/m^2 was similar to that of the reference cotton knitted fabric – 299 g/m^2.

All designs of underwear consisted of a long-sleeved shirt and full-length trousers, each of which was tested under protective clothing made of barrier material, tightly coated with PVC, consisting of a hooded jacket and long trousers.

***Table 1.** Characteristics of the clothing variants.*

Variants of clothing system tested	Protective clothing	Underwear
A1 reference variant	Hermetic clothing made of polyester-polyamide fabric coated with polyvinyl chloride	Underwear made of interlock cotton knitted fabric (surface mass: 299 g/m^2, thickness: 1,42 mm)
A2 model variant		Underwear made of fabric system: - a conductive-diffusive layer: pique-type knitted fabric made from textured PES yarn (surface mass: 127 g/m^2, thickness: 1,48 mm), - a sorptive layer: pique-type knitted fabric made of viscose yarn (surface mass: 188 g/m^2, thickness: 1,22 mm)

Clothing variants are described in ***Table 1.***

Test methodology

Two series of experimental tests (one set for variant A1 and one set for variant A2) were conducted, each one with 4 young, healthy volunteers aged 27 - 31 (average age - 29 years), in the body weight range of 66 - 83 kg (average body weight - 76 kg) and 169 -179 cm tall (mean height 174 cm), taking part in each series. The volunteers were informed about the experimental procedures. The Medical University Ethics Committee's approval was obtained.

Before commencement of the experiments, each test clothing user underwent a medical qualification including a physical examination, general medical examination, and essential laboratory blood and urine analyses.

All measurements were performed in a microclimatic chamber at 22 °C, with a relative air humidity of 40% and air flow velocity of 0.2 m/s. Each experiment lasted 75 min. and included an initial 10 min. of rest (in a sitting position), 60 min. of work on a cycloergometer with a 60 W load and a 5 min. regeneration period in the chamber under the same microclimatic conditions.

During the experiments in the climatic chamber, the following parameters were recorded to ensure the safety of the participants: the heart rate, arterial blood pressure, internal temperature, and ECG tracings. The experiment was continued until one of the following limits was reached: a core temperature of 38.0 °C, a heart rate of 80% of the individual maximum heart rate, 100% relative humidity measured at two places at least (under protective clothing), or objective or subjective signs of fatigue.

The comparative assessment of the clothing was based on the analysis of the microclimate under the clothing and near the skin, as well as subjective assessment of the clothing system tested by volunteers. The temperature and relative humidity under the clothing were monitored at four places (right chest, left shoulder, left arm, right thigh) every minute.

The following parameters were analysed:

- Temperature and humidity between the skin and underwear. The measurements were related to the temperature and humidity of the microclimate under the clothing, in which sensors did not touch the skin. Measurements were carried out at four places of the body: on the surface of the chest and back, as well as on the external surface of the arm and thigh using the Hygrometer LA8 humidity and temperature sensors manufactured by Rotronic AG (Germany). The accuracy of the sensors (3 × 30 mm) was (± 5%) in the range of relative humidity and ± 0.1 ºC in the range of temperature.

During the analysis of the results, absolute values of the temperature and humidity between the skin and undergarment were considered as well as their increase from the beginning to the end of the experiment.

In order to make the presentation more transparent, only increments of the humidity and temperature are presented in this article. It should also be emphasised that the initial valves of humidity and temperature related to the microclimate differed slightly between particular test persons. However, in the majority of cases, the average initial humidity was about 50 - 56%, and the temperature about 31 - 33 °C.

All the measurements were made in the sitting position. A view of a volunteer in hermetic protective clothing during the tests in the microclimatic chamber is shown in the photograph in ***Figure 2***.

Treatment of data

Statistical differences were determined using an analysis of variance of 0.05, taking the conditions of the test performance into account. The homogeneity of variance was checked using the Leven test.

Results and discussion

As expected, work in hermetic clothing protecting against chemicals caused an increase in the humidity and temperature of the microclimate under the clothing. Its characteristics varied and was dependent on the intensity of sweat secretion by the various skin areas. As was observed during the experiment, marked changes in the humidity and temperature of the microclimate took place on the back, chest, thigh and arm under the clothing near the skin. Apart from the changes in the humidity and temperature of the microclimate under the clothing, the increases in thesechanges were analysed as initial values, which sometimes varied due to the differences among individuals.

Humidity under the clothing increased the most rapidly on the back. After 30 min. of the experiment, the humidity of the protective clothing systems investigated reached the following: for A1 (the reference variant made of cotton) - 95%, and for A2 (model variant– two layer undergarment) - 84%, respectively. These differences were statistically significant ($p < 0.05$).

The humidity increase for A2 at the final stage of the experiment was ca. 28%, whereas for A1 it reached even 50%

***Figure 2.** Testing of protective clothing in a climatic chamber.*

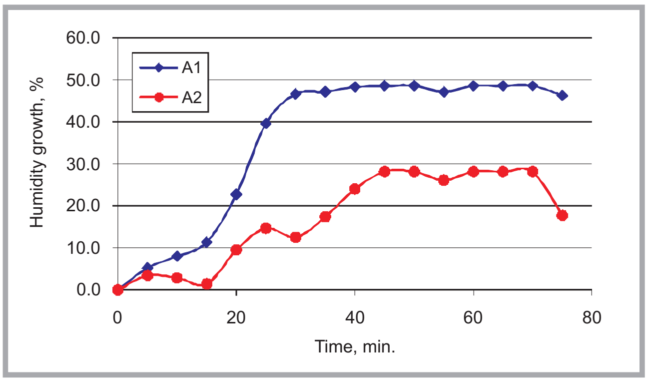

Figure 3. Dynamic of humidity growth in the microclimate on a back during the experiment in a climatic chamber.

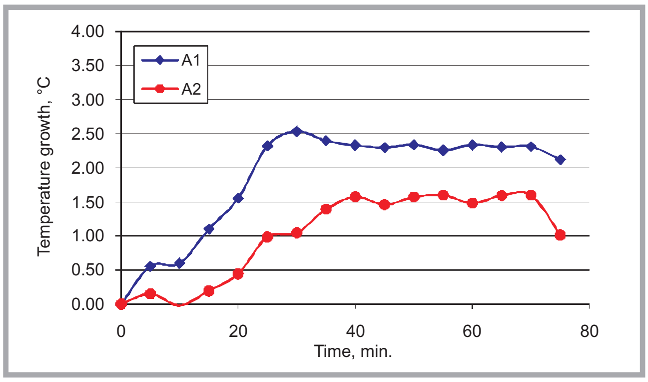

Figure 4. Dynamic of temperature growth in the microclimate on a back during the experiment in a climatic chamber.

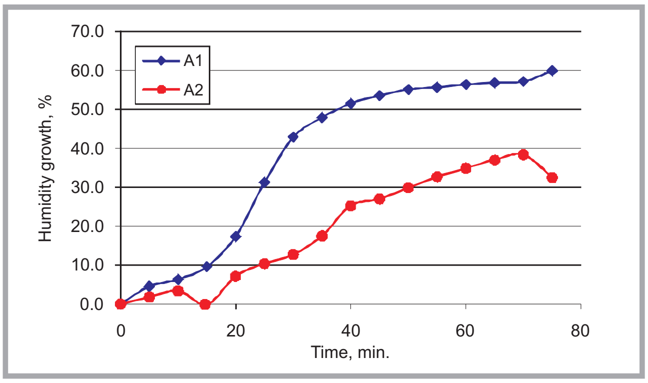

Figure 5. Dynamic of humidity growth in the microclimate on a chest during the experiment in a climatic chamber.

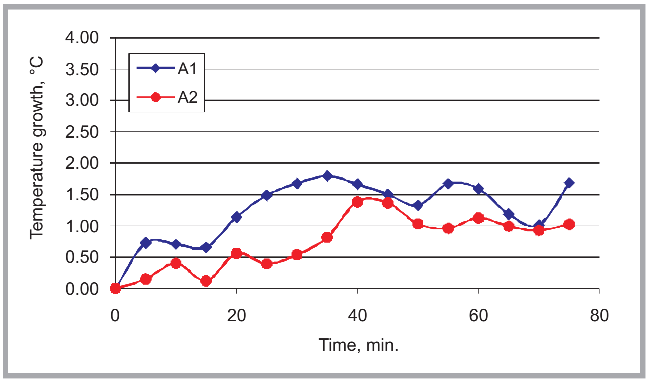

Figure 6. Dynamic of temperature growth in the microclimate on a chest during the experiment in a climatic chamber.

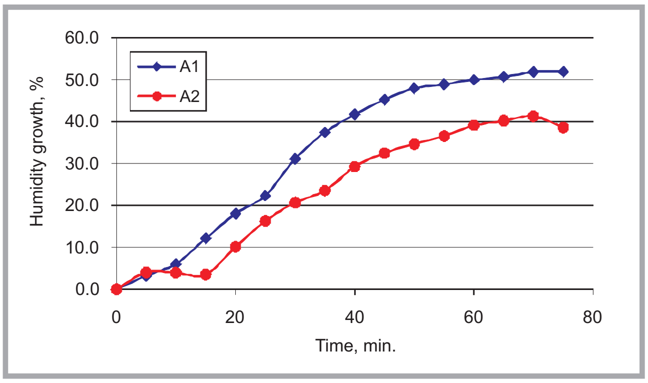

Figure 7. Dynamic of humidity growth in the microclimate on a left shoulder during the experiment in a climatic chamber.

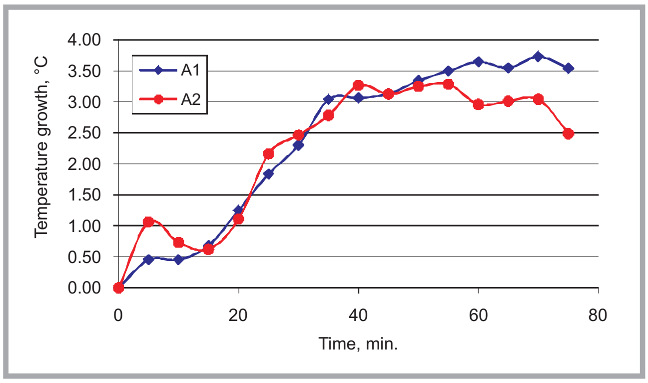

Figure 8. Dynamic of temperature growth in the microclimate on a left shoulder during the experiment in a climatic chamber.

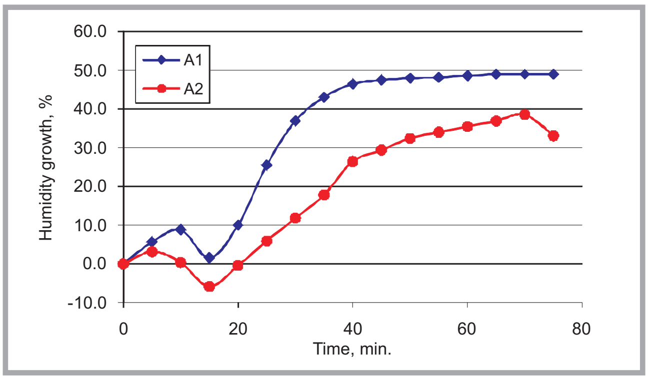

Figure 9. Dynamic of humidity growth in the microclimate on a left thigh during the experiment in a climatic chamber.

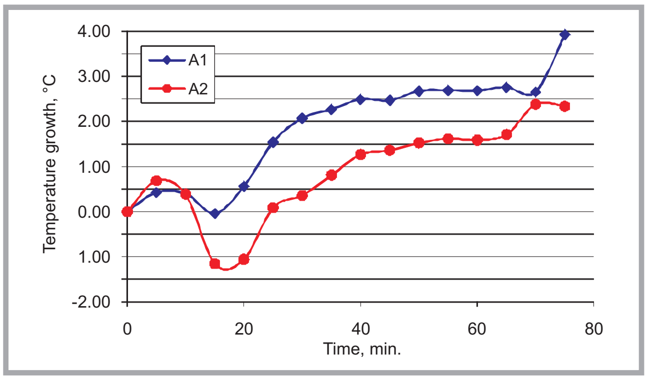

Figure 10. Dynamic of temperature growth in the microclimate on a left thigh during the experiment in a climatic chamber.

(***Figure 3***). The temperature increases measured for the microclimate over the back are presented in ***Figure 4***.

The changes in relative humidity on the chest under the test clothing were slower than on the back. Only for variant A1 was 100% relative humidity obtained in the last minutes of the experiment. For A2 the relative humidity of the microclimate increased very slowly. The increases in humidity are presented in ***Figure 5*** and temperature increases - in ***Figure 6***.

Similarly as for the back and chest, **the relative humidity on the left shoulder** changed very slowly for variant A2, reaching values lower than for A1. At the end of the experiment, the humidity for A1 reached 100% and for A2 only 91%. Those differences were statistically significant ($p<0.05$). The temperature levels for A1 and A2 were similar up to the 55th minute of the experiment. After that moment, a slight temperature decrease was noted for variant A2 and an increase for variant A1. The increases in relative humidity and temperature are presented in ***Figures 7*** and ***8***.

The analysis of **microclimatic changes under clothing on the left thigh** revealed that the relative humidity increased very quickly. In the 40th minute of the experiment, the humidity for variant A1 was already 98% and for A2 only 85%. Those differences were statistically significant ($p < 0.05$). At the end of experiment, the relative humidity for both variants was about 100%; however, the increase was lower for A2 than for A1 (***Figure 9***).The temperature increases were similar for A1 and A2 (***Figure 10***).

From the start of the experiments, subjective ratings of skin wetness were much worse with clothing A1 than with A2.

The results of relative humidity and temperature changes in the microclimate under hermetic clothing measured near the skin showed that structural and material differences in the underwear influenced the microclimate under the hermetic protective clothing. The use of the two-layer model of undergarment A2 (model variant) resulted in an improvement in microclimatic parameters. The humidity and temperature values, as well as their increases during the experiment were lower for this variant than for the reference one made of cotton.

The favourable influence of model underwear A2 on microclimate parameters is primarily due to high diffusion and then a sorption of liquid sweat by the system of fabrics used in this underwear. During the tests in the microclimatic chamber, the whole system of fabrics underwent continuous movement. At the contact places between the model multilayer underwear (PES/Viscose) and the skin, a high removal of sweat from the skin took place, making it dry. This favoured a reduction in microclimate humidity, making it possible for the sweat secreted to evaporate. As a result of placing polyester fibre knit, absorbing only small quantities of water vapour and sweat, next to the skin, it had contact with the dry surface of the undergarment fabric, which contributed to a reduction in microclimate humidity. After the experiment it was observed that the surface of the model two-layer underwear, being in direct contact with the skin, was dry unlike the rather damp surface of the cotton garment. The soft and elastic structure of the fabric system (pique-type weave) had an additional impact on the microclimate. The system used was in contact with the user's skin despite the placement of sensors on its surface.

The less favourable influence of cotton knitted underwear (A1) on the microclimate results from the fact that its ability to eliminate and absorb liquid sweat from the skin is not so high as that of the polyester and viscose knit systems. The wet surface of the cotton knit was in contact with the user's skin, which resulted in higher microclimate humidity than in the case of a dry surface touching the skin. Cotton knit, as follows from the instrumental studies of fabrics [12], is additionally characterised by lower water vapour sorption than the polyester-viscose system used in the model garment.

Conclusions

1. The tests of different kinds of underwear on volunteers in a climatic chamber showed a significant influence of the kind of underwear worn directly on the skin on the dynamics of sweat sorption, humidity and the temperature microclimate under hermetic protective clothing.
2. The favourable characteristics of the model of underwear proposed consist of a diffusive layer made of synthetic fibre (PES) worn on the skin, and an outer sorptive layer (Viscose). Both layers have different physical functions in shaping the microclimate and co-operate in the effective elimination of sweat from human skin. For the diffusive layers of underwear (situated directly on the body's skin), non-hygroscopic fibre could be proposed, especially textured polyester yarns. The material considered to be most favourable for the sorptive layer is viscose fibre. Textured knitted fabrics e.g. of the pique type, have very good parameters from the point of view of user comfort.
3. The results of the study have demonstrated that it is possible to reduce the discomfort in hermetic protective clothing associated with work by using specially designed underwear structures, actively participating in the elimination of liquid sweat from the skin and sorption of sweat vapour, consequently changing the parameters of the microclimate around the garment user's body in a positive way.

Acknowledgment

Publication presenting the results of research problem no 03.9.1 ,Combinations of materials improving biophysical parameters of protective clothing' – Long-term research program: Safety and Health Protection in Working Environment.

References

1. *Holmer I.; Ergonomics, 1, (1995) 166- 182.*
2. *Umbach K. H.; Chemiefasern, Textilindustrie, 8, (1980) pp. 628-636.*
3. *Wu H. Y., Zhang W. Y., Li J.; Fibres & Textiles in Eastern Europe 2009, Vol. 17, No. 4 (75) pp. 46-51.*
4. *Koradecka, D. Bugajska J.; Estimation of energy expenditure during manual on working stands, in Polish Warsaw 1998, Poland,Central Institute of Labour Protection.*
5. *Klonowicz S., Kozłowski S.; Człowiek i środowisko termiczne Warsaw, Poland, Państwowy Zakład Wydawnictw Lekarskich 1970.*
6. *Lehmann G.; Practical physiology of work, in Polish Warsaw, Poland Państwowy Zakład Wydawnictw Lekarskich 1966.*
7. *Beckett W. S., Davis J. E., Vroman N., Nadig R., Fortney S.; Journal of Occupational Medicine, 28 (6), 1986 pp. 411-414.*
8. *Haase J.; Prüfung und Bewertung der bekleidungshygienischen Eigenschaften von textilen Erzeugnissen, Textiltechnik 30, nr 5, 1980, pp. 314 -318.*
9. *Marszałek A., Sawicka A.; Impermeable protective clothing-wok time must be limited Fifth Scandynavian Synposium on Protective clothing – Proceedings, Denmark (1997).*
10. *Marszałek A., Bartkowiak G., Łężak K.; International Journal of Occupational Safety and Ergonomics (JOSE), Vol. 15, No. 1, 2009, pp. 61-73,*
11. *International Organization for Standardrization. Ergonomics - Evaluation of thermal strain by physiological measurements. (No ISO 9886:1992).*
12. *Yang K., Jiao M. L., Chen Y., Li J., Zhang W.; Fibres & Textiles in Eastern Europe 2008, Vol. 16, No. 3(68) pp. 51-55*
13. *Bartkowiak G.; Fibres and Textiles in Eastern Europe 2000, Vol. 8, No .4(31),pp.79-83.*
14. *Bartkowiak G.; Fibres and Textiles in Eastern Europe 2001, Vol. 9 No. 4, pp.41-45.*

Received 05.03.2009   Reviewed 10.11.2009