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SHAPING THE PHYSIOLOGICAL COMFORT PERFORMANCE OF MULTILAYER CLOTHING ASSEMBLIES FOR FIREFIGHTERS

Abstract

The aim of the Ph.D. work is to create theoretical bases enabling shaping the comfort-related properties of the multilayer clothing packages intended for the firefighter's protective clothing (FPC). The utility purpose of the research is to improve the thermo-physiological comfort of the firefighter when using protective clothing.

The thesis of the work is as follows:

Through an appropriate selection of materials in the multi-layer clothing assembly consisting of the protective clothing for the firefighter and underwear, it is possible to shape the properties of clothing assembly (firefighter's protective outfit) affecting the thermo-physiological comfort of the firefighter during their firefighting or other rescue actions.

This goal is intended to be achieved by analyzing the thermal insulation properties - thermal resistance and thermal absorptivity, as well as the ability to transport water-vapor and liquid moisture of the following textile materials:

- multi-layer textile packages intended for the FPC,
- knitwear intended for underwear for firefighters,
- multi-layer textile assemblies consisting of multi-layer textile packages for the FPC and knitted fabrics intended for underwear,

and then an analysis of the impact of the number and configuration of layers on the effectiveness of ensuring thermo-physiological comfort of the created multi-layer textile assemblies.

As part of the research, the state of knowledge on the subject of the thesis was reviewed based on a review of scientific literature. The review covered the issues such as working conditions and hazards in the working environment of firefighters, the structure and properties of protective clothing for firefighters, and the biophysical properties of textiles and clothing. Based on the literature review, it was founded that experiments of protective clothing for firefighters are the subject of numerous publications, primarily in the field of barrier properties of materials and clothing, by applicable standards. It has also been found that the biophysical properties of protective clothing for firefighters are also important for ensuring the efficiency of a firefighter. Previous studies on properties that influence thermo-physiological comfort, have been numerous but did not cover the issues of liquid sweat transport. It also stated that there are not any specific requirements concerning underwear for the firefighter. This is an important gap taking into account that the underwear is the next-to-skin layer of the firefighter's outfit in action.

In the theoretical part, considerations of the transport of heat and liquid moisture through multi-layer packages of textile materials were carried out. The general equations were formulated describing the thermal resistance of multilayer clothing and the transport of liquid moisture through multilayer textile materials during use.

The research part of the dissertation includes:

- experiment with multi-layer packages, knitted fabrics, and assemblies composed of multi-layer packages and knitted fabrics, in the scope of:
  - thermal insulation properties (thermal resistance, thermal absorption),
  - water vapor resistance and water vapor permeability,
  - liquid moisture transport,
- statistical analysis of experimental results in order to assess the influence of the number of layers and the type of materials in the assemblies on the biophysical properties of assemblies consisting of multi-layer packages and knitted fabric for underwear,

- application of the General Quality Index to quantify the quality of assemblies consisting of multi-layer packages for the firefighter and knitted fabric for underwear.

In general, there were tested:

- 4 multi-layer packages of protective clothing for firefighters, consisting of an outer shell, a middle layer constituting a barrier to moisture, and an inner thermal insulation layer with lining,
- 7 variants of knitted fabrics for underwear for firefighters, including an innovative knitted fabric made in the TransDry® technology and a specialist non-flammable knitted fabric for firefighter T-shirts,
- 28 multi-layer assemblies created by combining 4 multi-layer packages and 7 lingerie knits.

The following instruments were applied in the tests: Alambeta, Permetest, Moisture Management Tester M290, and MMT Fabric Stretch Fixture. Statistical analysis of the obtained research results was carried out using statistical tools available in the TBIC Statistica, Version 13.3 software: two-way analysis of variance (ANOVA) and non-parametric Kruskal-Wallis test.

The thermal insulation properties of the investigated textile materials and assemblies had tested using the Alambeta. The obtained results showed that the variant of the multi-layer packages for firefighter's protective clothing influences the values of thermal insulation parameters: thermal absorptivity and thermal resistance in a statistically significant way at the significance level of 0.05. The thermal resistance of multilayer sets is correlated with their thickness.

The thermal insulation properties of knitted fabrics for underwear also differ depending on the variant of the knitted fabric. The influence of the knitted fabric variant on the values of thermal insulation properties is statistically significant at the statistical significance level of 0.05. There is also a statistically significant correlation between thermal resistance and the thickness of knitted fabrics for underwear.

Clothing assemblies consisting based on multi-layer packages for firefighter's protective clothing and knitted fabric are characterized by various thermal insulation properties depending on the combination variant. Statistical analysis confirmed that both the variant of multi-layer packages for the FPC and the variant of knitted fabric for underwear significantly affect the thermal insulation properties of the assembly created at the significance level of 0.05. In the case of thermal resistance, the interaction between both independent variables is also statistically significant. The obtained results partially confirmed the theoretical considerations regarding the thermal resistance of the multi-layer textile barrier. However, there are some deviations from the theoretical assumptions. In most cases, the measured thermal resistance of multi-layer textile sets is lower than the one calculated as the sum of the thermal resistances of the multi-layer package and the knitted fabric. This is in line with previously published research and results from the surface roughness of textile materials and their flexibility. As a result, the contact area between the layers, through which the thermal flow occurs, may be larger than the nominal area of the adjoining layers.

The experiments of materials in terms of water-vapor permeability were carried out using the Permetest. As in the case of thermal insulation properties, water-vapor permeability and water-vapor resistance were tested on multi-layer packages for FPC and knitted fabrics for underwear. Due to the failure of the Permetest instrument, it was not possible to measure assemblies consisting of multi-layer packages and knitted fabric.

On the basis of the results of the water-vapor permeability of the investigated materials, it was found that multilayer packages for the FPC are characterized by a very high water-vapor resistance (28.5 - 117.5 mKm^2/W) and very low relative water-vapor permeability in the range of 7.6 - 21.5%. This means that they are unable to effectively transport sweat from the underwear surface to the outside. Especially, the transport of sweat will not be effective when firefighting or other rescue operations are accompanied by intense effort and stress.

The main barrier to the transport of sweat in the form of water vapor is the middle layer of the multilayer packages - a moisture barrier. The inner layers of the tested multilayer packages - thermal barriers connected to the lining, usually by quilting, are characterized by much higher relative water-vapor permeability. Due to this, sweat in the form of water vapor remains partly inside the structure of the clothing and partly condenses on the firefighter's skin. With this in mind, the ability of fabrics and materials for the FPC to wick away perspiration as a liquid should also be reviewed.

Protective clothing for firefighters is worn together with underwear. Underwear is the closest layer of a firefighter's protective outfit to the skin. Due to this, underwear is the first barrier to sweat produced by the body. As part of the thesis, experiments on the relative water-vapor permeability and water-vapor resistance of 7 variants of knitted fabrics that can be used in T-shirts for firefighters were carried out. The tests showed that all the analyzed knitted fabrics are characterized by very good relative water-vapor permeability in the range of 60.1% to 71.5% and low water vapor resistance in the range: of 2.6 - 4.0 mKm2/W.

When selecting materials for assemblies of the FPC, the interaction between the properties of underwear and protective clothing should be taken into account. Unfortunately, due to the failure of the Permetest, it was not possible to measure the water-vapor permeability of assemblies consisting of multi-layer packages for the FPC and knitted fabrics for underwear. Therefore, it was decided that in further experiments the water-vapor resistance of those multi-layer assemblies would be approximated based on the results obtained for multilayer packages for the FPC and knitted fabrics for underwear.

Liquid moisture transport experiments were performed using the Moisture Management Tester MMT M290. All textile materials and multilayer packages of the FPC being the subjects of analysis within the dissertation were subjected to the tests. In the case of multi-layer packages for the FPC, tests were performed for the whole packages and separately for the inner layer, and then the middle layer, which is a barrier to liquid moisture. The knitted fabrics were tested in a relaxed state and stretched at 15%. The

MMT Stretch Fabric Fixture was used to prepare samples with a specific stretch percentage.

Each variant of multi-layer packages for the FPC and each variant of knitted fabric for underwear presented different results in terms of liquid moisture transport properties. The liquid moisture wasn't observed on the outer layer of multi-layer packages for the FPC. Moisture transport in the form of a liquid was observed only in the inner layer of the package. Liquid moisture stays in the inner layer of the package and accumulates as the clothing is used. The highest value of the OMMC parameter (Overall Moisture Management Capacity) occurred for the inner layer of the SS4 variant (0.21), and the lowest (0.01) - for the inner layer of the SS2 variant.

In the case of knitted fabrics for underwear, the liquid moisture transport was different depending on the individual properties of the knitted fabric. According to the value of the OMMC parameter, the knitted fabrics were ranked from the best to the worst in the following order: KF5, KF4, KF1, KF6, KF2, KF3, KF7.

It was found that the stretch of knitted fabrics for underwear has a significant influence on the liquid moisture transport properties. 15% stretch resulted in an improvement in liquid moisture transport properties, however, it changed differently for each knitted fabric. The greatest improvement was shown for knitted fabrics KF2 (OMMC = 0.27 $\rightarrow$ 0.72) and KF3 (OMMC = 0.18 $\rightarrow$ 0.50). This can be explained by the fact that when the knitted fabric is stretched, its geometric structure changes, and the distance between the yarns increases, which improves its moisture transport properties.

It was found that both the variant of the multilayer packages and the variant of the knitted fabric, used in the created assemblies had a statistically significant influence on the liquid moisture transport properties of the assemblies, and there are statistically significant interactions between these two factors.

The best liquid moisture transport properties among the created multi-layer clothing assemblies are characterized by the following assemblies: SS4+KF4 (OMMC = 0.6305), SS3+KF5 (OMMC = 0.6201), SS4+KF2 (OMMC = 0.6197). The lowest OMMC value

was recorded for the assemblies: SS1+KF3 (0.0000), SS1+KF6 (0.0000), SS2+KF6 (0.000), SS3+KF6 (0.0000), SS4+KF6 (0.0000). The difference between the variants with the highest and lowest value of the OMMC parameter in the group of multi-layer clothing assemblies was 0.6.

The obtained results showed that through the optimal selection of the components of the firefighter's clothing assemblies, the properties of moisture transport through the clothing can be significantly improved, and thus the firefighter's work safety and comfort can be improved.

The assessment of the created multilayer clothing assemblies for firefighters was carried out using the *General Quality Index (GQI)* formula. It is a numerical index representing the general value of the product in the aspect of its quality. The applied method is a way of multi-criteria assessment of product quality. There are different formulas for quality indicators. In general, general quality indicators characterize the quality of materials or objects from the point of view of a specific group of characteristics.

In the presented work, in the first stage of the assessment, the General Quality Index was defined by the following formula:

$$GQI = \sum_{i=1}^{n} r_i$$

Where:

r_i – the rank of the i^{th} parameter taken into consideration,

n – the number of parameters under consideration.

In order to calculate the values of the General Quality Index, the following comfort-related properties were taken into consideration:

- thermal resistance,
- water-vapor resistance,
- Overall Moisture Management Capacity.

In the second stage of the assessment, a relative General Quality Index has been proposed, the value of which ranges from 0 to 1. This approach facilitates the

interpretation of the General Quality Index value and the assessment of the materials subjected to testing.

The following generalized equation for the relative General Quality Index has been proposed:

$$GQI_{rel} = \frac{\sum_{i=1}^{n} r_i}{n * m}$$

Where:

r_i – rank according to the i^{th} parameter (property),

n – number of parameters taken for calculation,

m – number of assessed assemblies (materials).

For the analyzed group of assemblies, the highest quality from the point of view of physiological comfort was stated for the SS4+KF4 and SS4+KF1 assemblies.

The low quality of the assemblies created based on the KF6 knitted fabric was surprising because the KF6 fabric was manufactured using special patented technology designed to improve the comfort-related properties of cotton fabrics.

Research has shown that the idea of the General Quality Index can be successfully used to compare and evaluate the quality of textile packages and clothing assemblies for FPC. It will allow for the optimal design and production of clothing for firefighters from the point of view of ensuring their comfort of use and improving work safety.

Based on the theoretical considerations and experimental research, it was found that,

- For the evaluated properties, thermal insulation properties, water vapor, and liquid moisture transport are the main properties that can fully express clothing comfort.
- The equipment used to measure the parameters of the thermo-physiological comfort properties of clothing materials and clothing was advanced and innovative, cooperating with specialized software enabling the determination of all relevant parameters.

- It has been proven that the optimal and appropriate selection of materials in the assembly for the FPC can significantly improve the comfort and protective properties of the clothing and improve the safety and comfort of the firefighter wearing protective clothing.
- The assessment of assembly quality for the FPC using the General Quality Index (GQI) is based on a theoretically developed method, and in the future, it is possible to evaluate the quality of other clothing with this method.
- The dissertation can serve as a reference guide for those researching on clothing quality assessment and clothing comfort properties.
- It was proved that by appropriate selection of the materials creating particular layers of the protective clothing outfit for the firefighters, it is possible to shape the comfort performance of the firefighter's clothing assembly.