MEASUREMENT OF PHYSIOLOGICAL PROPERTIES OF MILITARY CLOTHING IN SIMULATION OF CLIMATIC CONDITIONS IN SELECTED AREAS OF THE WORLD

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Abstract: *The paper presents results of measurements of selected thermal-physiological properties of military clothing fabrics in simulation of climatic conditions in selected areas of the world. The aim of the research was to test and compare old and new sandwich structures of military clothing and provide description of their basic characteristics relating to selected utility properties such as heat resistance R, thermal conductivity λ and vapour resistance Ret. The result of the research is delivery of suitable sandwich structures of clothing according to real climatic conditions, under which they are used. The results of experimental measurement allow to verify functionality and suitability of military clothing used in various areas of the world by objective measurement in simulation of real climatic conditions under European standard EN 60721-2-1:2014 that sets the types of climate characterized by the values of air temperature and humidity.*

Keywords: *physiological properties, thermal conductivity, heat resistance, water vapour permeability, textile sandwich, military clothing.*

1 INTRODUCTION

Physiological comfort of a person is closely related to transport of air and liquid humidity, heat transfer through individual clothing layers and air flow in clothing. Utility properties and comfort of clothing influence physical processes in clothing as well as interactions of clothing with user's skin and with environment. Good thermal and physiological properties of military clothing are important, particularly if they cannot be easily replaced or postponed as it is common in clothing intended for casual wear or fitness. Suitable construction solution of clothing that also influences how clothing while being worn is adapted and allows free move is also important [1]. By assessing physiological properties we endeavour for more authentic and accurate presentation of actual functional value of the textile and clothing product [2]. We comprehensively assess comfort of the clothing product depending on the reaction of human organism, climatic environment and clothing system, which the surveyed person is wearing. The clothing system of military clothing consists of several layers of individual military clothing. The main objective of clothing layering is to achieve synergy during transport of heat, humidity in individual clothing layers and to avoid occurrence of unpleasant feelings under the conditions of hotness, cold or humidity.

Reference [4] is primarily focused on the possibilities for objective assessment of selected thermo-physiological properties and touch of the first layer of clothing, which is in direct contact with user's skin. Final assessment of comfort is based on common assessment according to the index of comfort because the first layer of clothing must not only transfer heat and humidity from skin to textile surface (or to other textile layers) but the users must also have good feelings when their skin touches the clothing. If one of the clothing layers is chosen incorrectly, a non-functional layer ensues and then the whole system does not function. Long-lasting state of user's discomfort, e.g. a soldier who feels uncomfortable, has negative effect not only on user's performance while executing tasks but due to hypothermia or hyperthermia of organism; the user's health can be endangered. Due to variable temperatures in various areas of the worlds, layering of individual clothing components needs to be adjusted. The number of clothing layers differs and is adopted according to given climatic conditions and equipment requirements and protection of the user-soldier. Correct function of the clothing barrier layer is also important for correct function of the textile sandwich, particularly if exposed to adverse ambient conditions. Membrane of this layer must show not only good capacity to let vapour through but also to have sufficient resistance to pressure water effect [5].

2 PERFORMED RESEARCH ACTIVITIES

The research builds on previous experiment, in which the effect of sandwich structure of military clothing of the old and new types of layering on the properties of physiological comfort was solved. Thermal insulation properties were measured in individual samples of military clothing textiles and in layered sandwich were measured to verify the effect. Thickness and permeability of the material were measured too. Measurements were carried out in the laboratory of the Department of Clothing of the Textile Faculty at the Technical University in Liberec within processing of a partial aim of a diploma project when solving the issues of Innovation of Special Functional Clothing for Army [3].

All measurements were carried out in compliance with ČSN EN ISO under standard conditions for testing of textiles at the temperatures of 20°C and 65% relative humidity. Thermal insulation properties were measured by device FOX 314. Device FOX 314 is a heat flow meter from a company TA Instruments which is designed for measuring thermal conductivity. Air permeability tester SDL M021S and fabric thickness tester SDL MO34A both from a company SDL Atlas were used for a measurement air permeability of samples and for measurement thickness according ISO standards. More details about devices and their characteristics could be find out on a website of theirs manufacturers or in a datasheets.

Measurements proved that thermal insulation properties of the old and new types of military clothing layering were maintained. In the new type of sandwich in protective layer, utility properties such as waterproofing and resistance to water penetration were improved. These new properties affected air permeability of the third barrier layers of clothing and of the entire sandwich structure of military clothing. Results of the experiment implied that the jacket of TERMO 2010 type can be worn without protective layer, without the sandwich structure consisting of individual layers losing its function. The above stated ascertained facts prove that each individual material has its unique functional properties.

Such particular characteristics of individual clothing layers need to be known exactly and they need to be composed into the correct system of textile sandwich structure by layering according to the users'/soldiers' needs for given environment, where they will function. There are many other factors that influence thermal insulation properties of clothing. Besides already mentioned permeability of the textile, it is occurrence of humidity, particularly liquid humidity in the textile and in layers. Textile structure, its compressibility, filling and other parameters of the textile are also important. For correct function of the clothing, it is equally important to know and follow correct maintenance of special clothing so that the clothing keeps its utility properties.

3 MATERIALS AND METHODS

3.1 Methodology

The following experiment was proposed to verify ascertained material properties and assumption for achieving optimum comfort of military clothing in simulation under real climatic conditions at various areas of the world. Assessment of clothing focuses on the most important thermal-physiological properties of clothing, i.e. its thermal insulation properties and vapour resistance. Testing samples of new military clothing that are used under field conditions by Czech Army (hereinafter AČR) were used for the experiment. In Table 1, there is an overview of military clothing that were used and their material composition.

Table 1 Overview of used military clothing and their material composition and origin

Marking	Material name	Material composition	Producer
1	Light thermo 2012	85% functional polyester with silver ions content, 9% antistatic fibre, 6% polyamide	Monitex Czech s.r.o., Tabor
2	Hard thermo 2012	91 % functional polyester with silver ions content, 9% antistatic fibre	Monitex Czech s.r.o., Tabor
3	Undershirt, short sleeve	100% cotton	Sintex a.s.
4	Undershirt, long sleeve	82% cotton, 18% polyamide	Sintex a.s.
5	Shirt 2000	50% polyester, 50% cotton	Marlway, s.r.o.
6	Blouse 95	50% polyester, 50% cotton	Koutny spol. s r.o., Prostejov
7	Blouse ripstop	50% polyester, 50% cotton	Koutny spol. s r.o., Prostejov
8	Sweater 95	30% wool, 70% polyacrylonitrile	Blazek Praha a.s.
9	Insert thermo	100% polyester	Jitex Comfort s.r.o., Pisek
10	Jacket thermo 2010	45% polyester, 45% polyamide, 10% elastane	Goldeck Textil GmbH, Austria
11	Coat 95	51% polyester, 49% cotton	Otavan Trebon, a.s.
12	Coat insert	100% polyester	Otavan Trebon, a.s.
13	Jacket ECWCS 2000	Top layer 100% polyamide, climatic membrane 100% PTFE (polytetrafluorethylene), under layer is laminate with a layer of lining knit of 100 % polyamide	Vyvoj, odevni druzstvo v Tresti
14	Jacket ECWCS 2012	Top layer 100% polyamide, climatic membrane 100% PTFE (polytetrafluorethylene), under layer is irregular polymeric coating of 100% polyamide	Goldeck Textil GmbH, Austria

If we think of possible deployment of the AČR troops in all areas of the world except Arctic areas, we will work with four climatic types in compliance with ČSN EN 60721-2-1 (038900) [6]. The standard sets the types of climate characterized by the values of air temperature and humidity. In Table 2, there are the input values of environment simulation for measurements of thermal insulation properties according to the type of selected climate listed.

Table 2 Input values of environment simulation for measurement of thermal insulation properties according to the type of selected climate

Type of climate	Temperature of lower board [°C]	Temperature of upper board [°C]
Cold	35	-20
Temperate	35	5
Arid	35	10
Tropical	35	20

Thermal conductivity of the material represents capability of the material to conduct heat under given conditions. Heat resistance is capability of the material to resist to heat transmission. So a good thermal insulation material has low thermal conductivity and high heat resistance. On Figure 1, there is device FOX 314 used for measuring of thermal conductivity of the samples of sandwich materials.

Figure 1 Machine FOX 314 for measurement the thermal properties of materials

Temperature of lower board of the FOX device simulates temperature of human skin and temperature of upper board simulated temperature of the environment according to selected climate. For calculation of thermal insulation properties of textile sandwich it is necessary to know thickness of the material. Thickness of material *t* [mm] was ascertained using digital thickness gauge SDL MO34A according to ČSN EN ISO 5084 (800844) - determination of thickness of textiles and textile products. Contact pressure was set at 70 Pa in accordance with the standard [7]. To measure the values of thermal flux the values of thermal conductivity λ [W/(m.K)] and heat resistance R [(m^2.K)/W] were counted. In Table 3, there are formulas for calculations of thermal conductivity and thermal resistance. The resulting value of thermal insulation of clothing is set using the calculation of heat resistance of textile sandwich (see Table 3) and it is expressed in the unit called 'CLO', where 1 clo equals to 0.155 [(m^2.K)/W]. In the thermal comfort standards it is recommended to use clothing with 1 clo in winter conditions and 0.5 in summer conditions under standard conditions at the temperature of 21°C, air flow of 0.1 [m/s] and relative humidity < 50%.

Table 3 Formulas for calculation of thermal conductivity λ and thermal resistance R (User Manuals FOX 314)

Formula for calculation	Description of the quantity and properties
$U1 = \lambda L \times 10$	U1 – value of thermal flow through the sample + air [W/(m^2.K)] λL – thermal flux of the lower board [W/(m^2.K)]
$U2 = \frac{Ubp \times U1}{Ubp - U1}$	Ubp ≈ 6.67 [W/(m^2.K)] U2 – heat permeability through the sample [W/(m^2.K)]
$\lambda = U2 \times \frac{t}{1000}$	λ – thermal conductivityof material [W/(m.K)] t – thickness of material [mm]
$R = \frac{1}{U2}$	R – thermal resistance of textile sample [m^2.K/W]

Water vapour resistance *Ret* [m^2.Pa/W] was measured using Sweating Guarded Hotplate (hereinafter SGHP) according to ISO 11092 [8]. Model 8.2 is located in the laboratory of the Department of Clothing. It was developed by Measurement Technology Northwest, Seattle, USA (hereinafter MTNW USA) and it is designed for measuring of thermal insulation properties (heat resistance *Rct*) and resistance to water vapour (vapour resistance *Ret*) of textiles and other materials according to ČSN EN 31092, ISO 11092 [8] and ASTM F 1868 in their entirety [9]. Overall view of the SGHP device built in climate chamber Vötsch VC 0018 is in Figure 2 and detail of the SGHP device is in Figure 3.

Measured lower Ret value indicates better utility properties of the material. Material has better capability to let vapour through, i.e. material resists less to water vapour penetration. So we can deem the measured values of textile sandwiches *Ret*<6 excellent and the values of *Ret*<12 good and the values of *Ret*<20 sufficient. The value of *Ret*>20 represents an almost non-permeable material.

3.2 Clothing used for the experiment

Based on comparison and analysis of used kinds of clothing and knowledge of the AČR members from previous foreign missions, 13 types of the systems of layering military clothing (hereinafter "sandwiches") for experimental measurement were identified. Two types of sandwich can be used for cold and temperate types of climate. 3 kinds of sandwiches were identified for cold type of climate, 5 kinds of sandwiches were identified for temperate type of climate, 2 kinds of sandwiches were identified for arid type of climate and 5 kinds of sandwiches were identified for tropical type of climate. The sandwiches consist of fourteen parts of military clothing that are layered on each other as required for given climatic area. Combination of different types of military garments including comparison of new and old type of a sandwich of clothing is in Table 4. It is evident that the new type of clothing layering for a cold climate contains one layer of the clothing less than in the old type.

Figure 2 The SGHP 8.2 device located in climate chamber Vötsch VC 0060

Figure 3 Detail of the SGHP 8.2 device

4 RESULTS AND DISCUSSION

Based on the methodology suggested, measurement of thermal-physiological properties of the sandwiches made of the military clothing material stated in Table 1 was carried out. Measured results of the experiment in simulation of real climatic conditions in various areas of the world are stated in Table 5. Stated results of the thermal conductivity, water vapour resistance are the average of three samples and are stated with the accuracy of 4 decimal places. Based on the values measured using the FOX device, thermal resistance of textile sandwich samples was set and dimensionless quantity of clothing insulation CLO was calculated. Resulting values for individual textile sandwiches of clothing are stated in Table 5.

Table 4 Type and combination of military garments used for measuring of textile sandwich divided according type of climate

Type of climate	Sandwich type	Combination of garments (marking- name), according layers of clothing					Sandwich thickness under load 70 [Pa] t [mm]
		1st Layer	2nd Layer	3rd Layer	4rd Layer	5th Layer	
Cold	A-Old type	4-Undershirt, long sleeve	8-Sweater 95	6-Blouse 95	12-Coat insert	11-Coat 95	17.48
	B-New type	1-Light thermo 2012	2-Hard thermo 2012	10-Jacket thermo 2010	14-Jacket ECWCS 2012		4.55
	C-New type	1-Light thermo 2012	2-Hard thermo 2012	9-Insert thermo	13-Jacket ECWCS 2000		6.08
Temperate	B	1-Light thermo 2012	2-Hard thermo 2012	10-Jacket thermo 2010	14-Jacket ECWCS 2012		4.55
	C	1-Light thermo 2012	2-Hard thermo 2012	9-Insert thermo	13-Jacket ECWCS 2000		6.08
	D	1-Light thermo 2012	2-Hard thermo 2012	10-Jacket thermo 2010			4.1
	E	4-Undershirt, long sleeve	8-Sweater 95	6-Blouse 95			6.15
	F	4-Undershirt, long sleeve	2-Hard thermo 2012	6-Blouse 95			3.17
Arid	G	1-Light thermo 2012	2- Hard thermo 2012	7-Blouse ripstop			2.32
	H	1-Light thermo 2012	2-Hard thermo 2012	6-Blouse 95			2.54
Tropical	I	3-Undershirt, short sleeve	7-Blouse ripstop				1.07
	K	1-Light thermo 2012	7-Blouse ripstop				1.17
	L	5-Shirt 2000	7-Blouse ripstop				0.87
	M	3-Undershirt, short sleeve	6-Blouse 95				1.28
	N	1-Light thermo 2012	6-Blouse 95				1.46

Table 5 Measured and calculated values of made textile sandwiches of military clothing for selected types of climate

Type of climate	Sandwich type	Vapour resistance *Ret* [(m^2.Pa)/W]	Thermal conductivity *λ* [W/(m.K)]	Thermal resistance *R* [(m^2.K)/W]	Clothing insulation CLO [-]
Cold	A	44.9470	0.0366	0.4782	3.09
Cold	B	**28.2147**	0.0256	0.1775	**1.15**
Cold	C	32.2843	0.0297	0.2047	1.32
Temperate	B	28.2147	0.0263	0.1730	1.12
Temperate	C	32.2843	0.0304	0.1989	1.28
Temperate	D	**11.9686**	0.0298	0.1375	**0.89**
Temperate	E	19.1776	0.0382	0.1611	1.04
Temperate	F	**11.1580**	0.0339	0.0934	**0.60**
Arid	G	**9.1494**	0.0293	0.0791	**0.51**
Arid	H	10.2198	0.0317	0.0802	0.52
Tropical	I	**5.1906**	0.0247	0.0432	**0.28**
Tropical	K	**5.3310**	0.0312	0.0374	**0.24**
Tropical	L	5.5925	0.0251	0.0346	0.22
Tropical	M	7.0702	0.0299	0.0428	0.28
Tropical	N	7.0311	0.0316	0.0462	0.30

4.1 Clothing insulation

Dimensionless quantity ‘CLO’ reaches, depending on the type of clothing, various values and under common conditions it typically ranks between the values of 0-2 [-]. The value of 1 clo represents thermal balance at ambient temperature of 21°C. For example the value of 0 clo is stated for naked body, 0.6 clo for summer clothing, 2 clo for skiing equipment, 3 clo for light polar equipment, 4 clo for hard polar equipment. Required values of clothing insulation clo for achieving the thermal balance and feeling of comfort depends not only on ambient conditions but also on occurrence of humidity, physical activity, i.e. production of heat and other conditions.

Measured values of clothing insulation clo stated in Table 5 are only slightly different for arid type of sandwiches number 7, 8 that achieve insulation of c. 0.5 clo and for tropical type of climate of sandwich number 9-13 that have clothing insulation at the level of 0.2-0.3 clo. More significant differences in clothing insulation according to clo are shown in textile sandwiches tested for temperate type of climate that rank from 0.6 clo to 1.28 clo. The above stated clo values comply with the requested value of insulation according to the standard and with conditions and type of climate, in which they are commonly used. The CLO values of insulation for textile sandwiches number 2 and number 3 tested for cold type of climate are low/insufficient and reach only the values of 1.15 and 1.32 clo. Only the old type of sandwich number 1 consisting of 5 layers shows sufficient insulation of clo at the level of 3.09. Sandwich number 1, however, does not comply with regard to low vapour permeability. No significant difference in clo clothing insulation in sandwiches No. 2 and No. 3 for two different types of climatic conditions was recorded at the experiment.

4.2 Water vapour resistance of textile sandwiches

Low vapour resistance of the clothing is important for achieving good comfort of the user while wearing the clothing. So a decisive utility property for reaching optimum comfort while wearing the clothing is low value of water resistance of textile sandwich *Ret* [(m^2.Pa)/W]. Based on this requirement, the most suitable type of clothing sandwich for given climatic conditions is clothing with as low vapour resistance *Ret* [(m^2.Pa)/W] as possible. In subsequent Table 6, there are the most suitable sets of the clothing textile sandwiches for individual climatic conditions selected according to this criterion.

Table 6 The most suitable types of the textile sandwiches of clothing according to thermal insulation CLO [-] and vapour resistance *Ret* [(m^2.Pa)/W]

Type of climate	Sandwich type	Vapour resistance *Ret* [(m^2.Pa)/W]	Clothing insulation CLO [-]
Cold	B	28.2147	1.15
Temperate	D	11.9686	0.89
Temperate	F	11.1580	0.60
Arid	G	9.1494	0.51
Arid	H	10.2198	0.52
Tropical	I	5.1906	0.28
Tropical	K	5.3310	0.24

5 CONCLUSIONS

The decisive utility property inevitable for reaching good comfort of the user while wearing military clothing under various climatic conditions is particularly low water vapour resistance of clothing *Ret* and, with regard to ambient conditions, sufficient insulation of clothing during given activity of the user.

Particularly in the areas, where increased emphasis is in thermal insulation properties of clothing such as the areas of temperate and cold zones, good thermal insulation capacities of clothing are, besides low vapour resistance of clothing, important requirements for clothing. Another requirement for clothing is resistance to external weather adverse effects, particularly water waterproofness, i.e. resistance to pressure water. Assuming that layers of clothing are selected properly, lower number of clothing textile layers means achieving better vapour permeability through clothing, i.e. lower vapour resistance *Ret*. The other way round, higher number of clothing layers leads to better thermal insulation property of clothing. However, with higher number of clothing layers the vapour permeability worsens and there is a risk of dew point origination. Vapour condensation in inner layers of clothing or directly on barrier layer of clothing subsequently causes further worsening of vapour permeability and overall decreasing of user's comfort.

Based on comparison of selected textile sandwiches of military clothing and comparison of two of their utility properties - vapour resistance *Ret* [(m^2.Pa)/W] and clothing insulation CLO [-], we can recommend the following combinations of clothing for individual zones:

- For tropical zone: sandwich type I (Light thermo 2012/ Blouse ripstop).
- For arid zone sandwich type G (Light thermo 2012/ Hard thermo 2012/ Blouse ripstop).
- For temperate zone sandwich type D (Light thermo 2012/ Hard thermo 2012/ Jacket thermo 2010).
- For cold zone sandwich type B (Light thermo 2012/ Hard thermo 2012/ Jacket thermo 2010/ ECWCS 2012). However this type has relatively low thermal insulation, which is given by its small thickness of only 4.55 [mm].

Selection of suitable (optimal) parameters, i.e. the ratio of utility properties '*Ret'* and 'CLO', is very individual and it depends on other conditions such as, e.g. planned application of clothing and period for using clothing, and so each of the types of sandwiches mentioned herein has its alternative stated in Table 6 or 5 allowing suitable selection of clothing according to specific requirements and preferences. Water vapour permeability, i.e. low vapour resistance '*Ret'*, is the most important utility property for highly functional clothing and that is why it determines suitability of selection of individual layers of clothing.

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