(REFEREED RESEARCH)

THERMAL CONDUCTIVITY AND RESISTANCE OF NOMEX FABRICS EXPOSED TO SALTY WATER

TUZLU SUYA MARUZ KALAN NOMEX KUMAŞLARIN ISIL İLETKENLİĞİ VE DİRENCİ

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ABSTRACT

The most important parameters characterizing thermophysiological comfort of clothing are thermal conductivity and thermal resistance. Protective and sport clothing is often used in wet state, which influences their comfort properties. Wet state of clothing can be caused due to the absorption of sweat or moisture from humid environment. This effect was particularly applies to people staying on the sea - sailors, seamen as well as marine soldiers. In this paper, Alambeta fast working PC controlled tester, was used for determination of thermal resistance and thermal conductivity of five different woven fabrics and one knitted fabric containing 93-100% of Nomex fibres, both in dry and wet state. Moreover, the effect of salinity of real sweat or sea water was simulated, by adding 1%, 2% and 3% of salt into the testing liquid (distilled water). As follows from the original results, even small content of the sodium chloride salt influences thermal comfort properties of the wetted fabrics.

Key Words: Thermal conductivity, Thermal resistance, Nomex fabric, Wet state, Salty water.

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1. INTRODUCTION

In last decades, increased attention is paid to comfort properties of textiles and garments. Thermal comfort is defined as a condition of mind which expresses satisfaction with the thermal environment. Thermal comfort implies the maintenance of the body temperature within relatively small limits (average skin temperature 32-34^{o}C). The value of microclimate parameters depends on the amount of heat produced by the body and the conditions of heat exchange with the environment. Under the conditions where the thermal comfort cannot be achieved by the human body temperature regulation, for example, in various combinations of environmental conditions, very cold or hot weather, and at different physical activity, clothing must be worn to support the temperature regulation by resisting and facilitating the heat exchange between the human body and the environment (1, 2). This is why the clothing should provide a proper barrier between the skin and the environment, which affects the heat transfer by conduction, convection, radiation and latent heat transfer by convection given by moisture evaporation or condensation. In the dry state, the majority of semi-permeable materials usually guarantee a satisfactory level of thermal properties, but when the garment is used in extreme wet conditions, the transfer properties of fabrics may change due to the increase of their moisture content. In these cases the final thermophysiological comfort is given by two principal components: thermal resistance in wet state and the active cooling resulting from the moisture evaporation from the skin and passing through the garment and from direct evaporation of sweat from the fabric surface (3). There are many fundamental papers dealing with fabric thermal properties, but just few of them take into consideration the aspects of the moisture content of fabrics (4 - 6). An equally important issue is the composition of moisture. Moisture stored by garment as a result of the absorption of sweat, or as a result of the absorption of moisture from humid environment, is not pure water but also contains other ingredients. According to the concept Kolesnikova (7), one of the explorers of polar clothing, when we are wearing clothing followed a saturation of the skin products (including sweat), which causes a decrease in insulation. Sweat is a clear, colourless liquid secreted by the eccrine sweat glands which lie in the dermal layer of the skin. It consists primarily of water (~99%) and salt, fats, urea, lactic acid, carbohydrates, minerals (such as potassium, calcium, magnesium, iron). An indication of the minerals content is sodium (0.9 g/l), potassium (0.2 g/l), calcium (0.015 g/l), magnesium (0.0013 g/l) (8).

In the case of the absorption of moisture from the external environment, the composition of moisture will depend on where in the world the garment is used. Here, the most extreme is sea and ocean environment. The characteristic feature of the sea is salinity. Salinity of sea water depends on a number of geographical factors. First of all, the climate - very high in hot and dry areas, where due to low supply of rainwater and high evaporation followed by collection of the salt, while low - in the cold zone (polar). It also depends on the position of the sea (open - the higher the salinity, inland - lower salinity), and the number of tributaries (rivers) and the level of pollution (especially in coastal areas). The average salinity of the seas and oceans at the equator is 35‰, the area of the tropics have a salinity in excess of up to 37‰, and the circumpolar regions below 32‰. (9, 10).

The paper presented the study on the impact of moisture on thermal parameters of fabrics designed for special clothing apparels. Using the device Alambeta, the thermal conductivity and the thermal resistance of selected Nomex fabrics in dry and wet state were determined. Moreover, the effect of salinity of real sweat or sea water was simulated, by soaking the samples in aqueous salt solutions having a concentration of 1%, 2% and 3%.

2. MATERIALS AND METHOD

As a testing material Nomex fabrics and their blends with Kevlar and carbon fibers were used. Their specification is shown in Table 1. Their parameters were measured in a laboratory with the temperature of 21-23ºC and 50-55% relative humidity.

Nomex® fibres [poly (-1,2-fenylodiamid)] are a family of highly heat-resistant, flame resistant aramid fibres invented and produced by DuPont. The high level of protection is engineered into the molecular structure of the fibre and does not come from chemical treatment. These fabrics and their blends with KEVLAR and carbon fibres are designed for thermo-resistant, non-flammable protective clothing (11). However, only few publications on their thermal comfort in the wet state have been published and no one took into account the factor of salinity clothing.

The research was carried out on the Alambeta device, which is enables the measurement of the following thermal parameters: thermal conductivity, thermal absorbtivity, thermal resistance and sample thickness. This device basically simulates the dry human skin and its principle depends in mathematical processing of time course of heat flow passing through the tested fabric due to different temperatures of bottom measuring plate (22°C) and measuring head (32°C). When the specimen is inserted, the measuring head drops down, touches the fabrics and the heat power levels are processed in the computer and thermophysical properties of the measured specimen are evaluated. The measurement lasts several minutes only. Thus, reliable measurements on wet fabrics are possible, since the sample moisture during the measurement keeps almost constant (3 - 5,12).

The simplified mathematical model for thermal conductivity λ includes just conductivity of fabric and water. In this model, the space filled by air will be replaced by water. The separated polymer and air effects on resulting thermal resistance and conductivity are not considered, as it has no sense: they cannot be measured precisely, due to strong effect of the structure. On the other hand, thermal characteristics of fabrics can be measured very precisely. Total thermal resistance is of single layer wet fabrics is believed to be a parallel link of thermal resistance of textile R_T and thermal resistance of water R_w, due to presence of continuing water-filled channels between the fabric surfaces (3).

For the simplest thermal model, involving the only parallel combination of thermal resistances, it is possible to sum up the related conductivities of the dry fabric (λ_d) and thermal conductivity of water (λ_W), but as the weighted sum only. Moreover, it should be neglected, that the presence of water in the fabric would reduce the fabric porosity, thus increasing thermal conductivity of the dry fabric λ_d.

Table 1. Specifications of the tested fabrics

No.	Name of fabrics	Type	Raw material	Weight, gm^{-2}	Thick., mm	Density of threads, dm^{-1}	
						warp	weft
1	Nomex Comfort 190	woven, 2/1 twill	93% Nomex / 5% Kevlar/ 2% carbon fibre	190	0.56	350	280
2	Nomex Comfort 220	woven, 2/1 twill	93% Nomex / 5% Kevlar/ 2% carbon fibre	220	0.54	371	279
3	Nomex Com-fort NX Delta	woven, 2/1 twill	93% Nomex / 5% Kevlar/ 2% carbon fibre	265	0.52	290	200
4	Nomex Com-fort FC Navy	woven, 2/1 twill	100% Nomex	220	0.62	290	250
5	Nomex III Paris Blue	woven, 3/1 twill	95% Nomex / 5% Kevlar	260	0.44	400	230
6	Nomex Hydro	knit, interlock	93% Nomex/ 5% Kevlar/ 2% carbon fibre	220	1.42	120	160

Fortunately, when considering the relatively high thermal conductivity of water, the effect of $\Delta\varepsilon$ on fabric thermal conductivity λ_d should be low. In this case, when considering the dry fabric mass (and surface) as 1 (100%) and the moisture content U lower then 1 (<100%), the next relationships may characterise thermal resistance of wet fabrics R_{RES} (3, 4):

$$\lambda_{RES} = (\lambda_d + U\lambda_W)/(1+U) \quad (1)$$

$$R_{RES} = h / \lambda_{RES} \quad (2)$$

where:

U - the relative mass of the moisture [%] related to the mass of the fully dry fabric,

λ_d - thermal conductivity of the dry fabric [W/m/K],

λ_W - thermal conductivity of water, [W/m/K],

ε - geometrical porosity of fabric, [m^3/m^3],

λ_{RES} - thermal conductivity of wet fabric, [W/m/K],

R_{RES} - thermal resistance of wet fabric, [m^2K/W].

3. RESULTS AND DISCUSSION

All fabrics were tested in various states of moisture content: 1 - normal state, 2 -“ultra-dry” and 3 - wet state (various). At the beginning the samples were dried in an air conditioner at 105°C ± 0,2°C, in order to get rid of all moisture. Then the samples were consequently soaked in their full volume of water to increase their humidity. In the research used 4 types of bath: water without salt and aqueous salt solutions, having respectively a concentration of 1%, 2% and 3%. During the measurement procedure, each sample before each measurement was stepwise softly mechanically dried to remove excess water and then weighed.

Figures 1 to 6 presented the experimental results of the influence of moisture and the concentration of salt in the water solution on the thermal properties of the exemplary tested Nomex fabrics (sample No. 2, 4 and 6). While Figures 7 to 9 show the comparison of thermal conductivity of all tested Nomex fabrics at 5%, 30% and 50% moisture content.

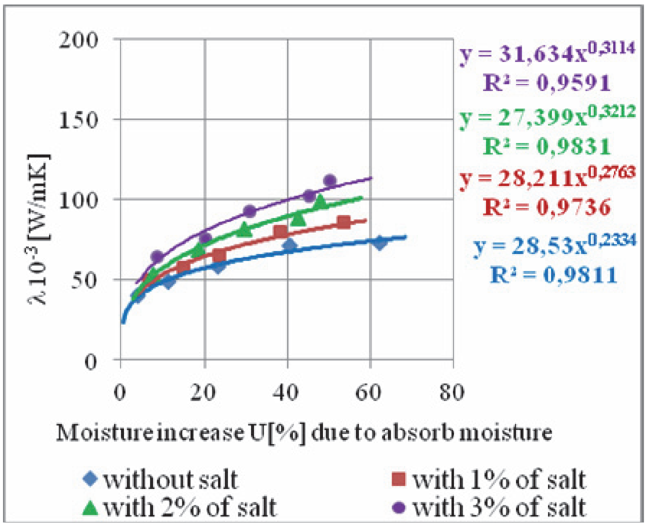

Figure 1. Effect of moisture content on thermal conductivity of the Nomex Comfort 220 fabric.

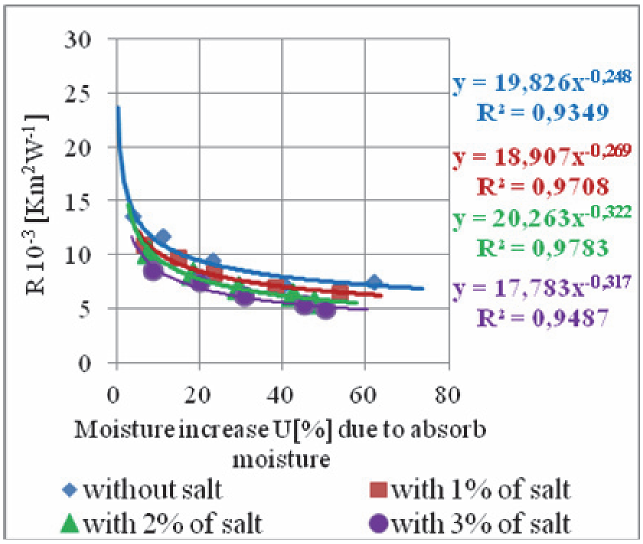

Figure 2. Effect of moisture content on thermal resistance of the Nomex Comfort 220 fabric.

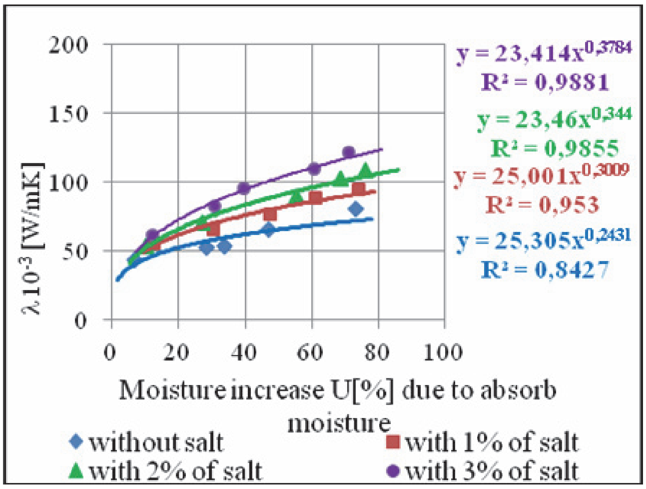

Figure 3. Effect of moisture content on thermal conductivity of Nomex Comfort FC Navy fabric

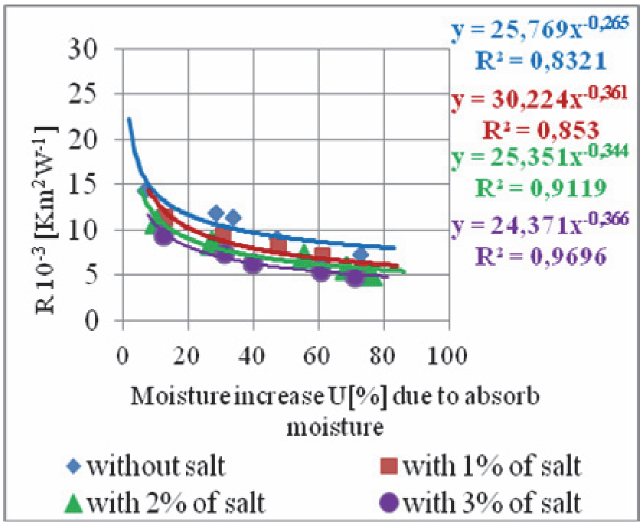

Figure 4. Effect of moisture content on thermal resistance of Nomex Comfort FC Navy fabric

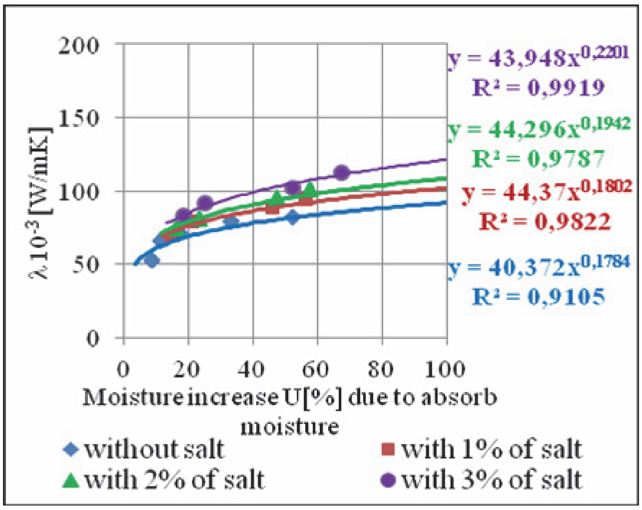

Figure 5. Effect of moisture content on thermal conductivity of Nomex Hydro fabric

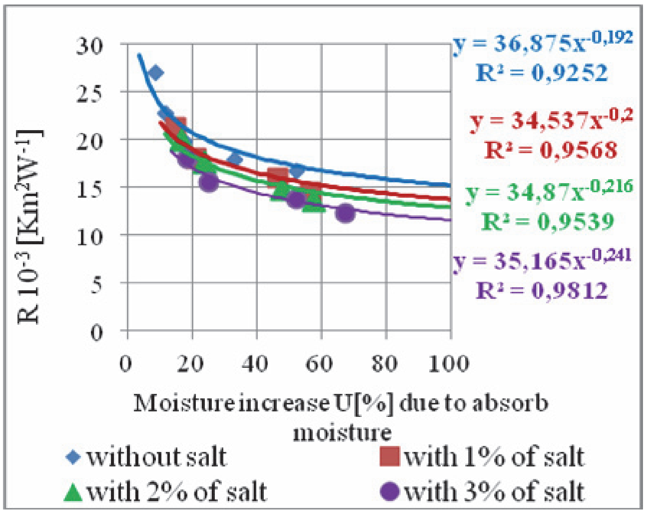

Figure 6. Effect of moisture content on thermal resistance of Nomex Hydro fabric

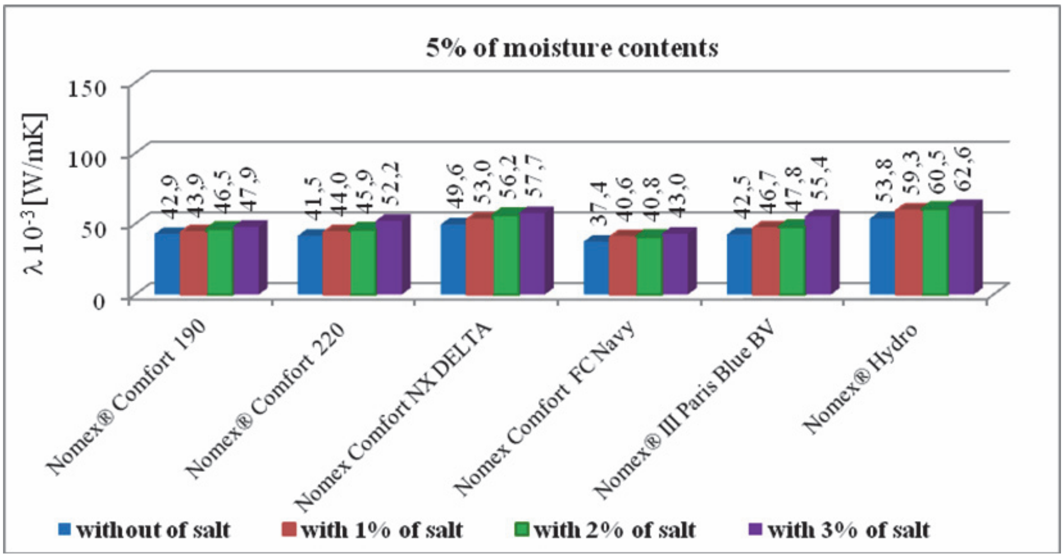

Figure 7. Thermal conductivity of all tested Nomex fabrics at the 5% moisture content.

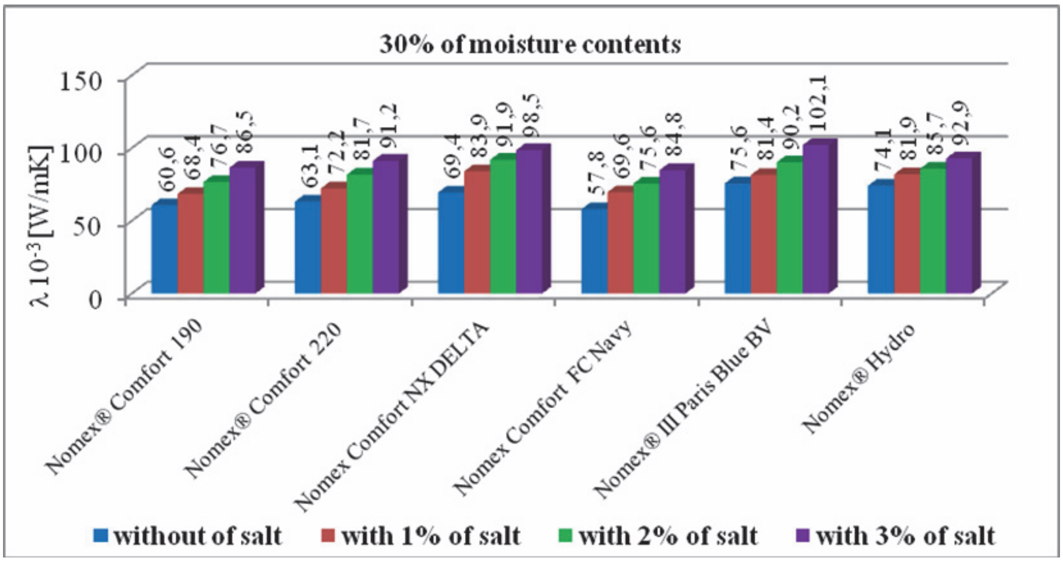

Figure 8. Thermal conductivity of all the tested Nomex fabrics at the 30% moisture content.

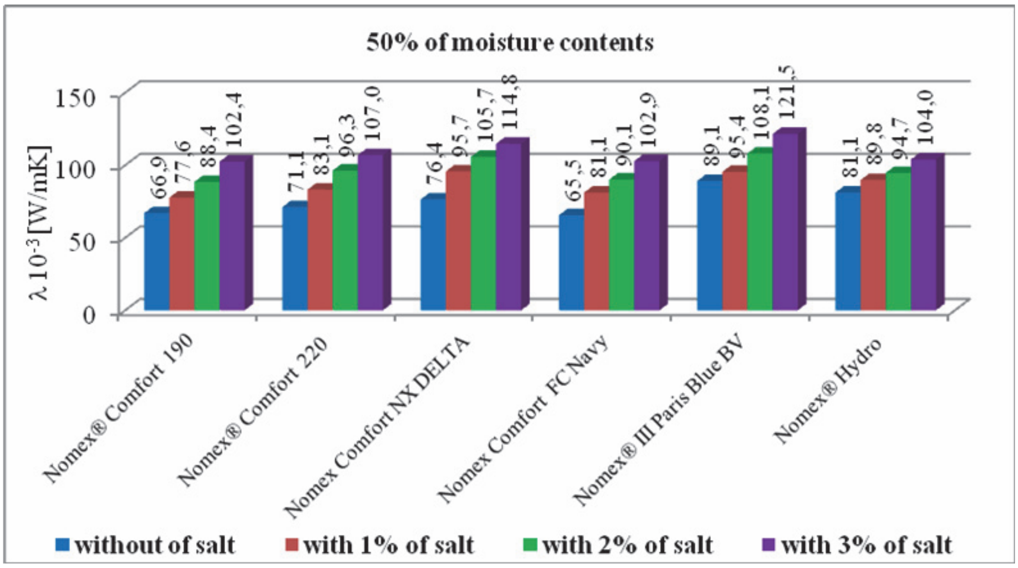

Figure 9. Thermal conductivity of all the tested Nomex fabrics at the 50% moisture content

From Figure 1 to 6 follows, that with the increasing moisture percentage in the fabrics thermal their conductivity (λ) increases and their thermal resistance (R) according to the Equation (2) naturally decreases. All the relationships were expressed by the power series curves. However, analyzing them more accurately, it can be concluded that in the first phase of fabric wetting their thermal conductivity (λ) the increase is steep, almost linear function of the moisture content (the phase of filling the macropores with the water), whereas after reaching a certain saturation level of about 15-20%, the next increase is much slower. The dependence of thermal resistance (R) on the increasing moisture content of the fabric exhibits the inverse behaviour.

As follows from the Figure 7, 8 and 9, the addition of sodium chloride salt into the liquid phase deteriorates the thermal properties, causing an increase of thermal conductivity of wetted fabrics and reducing substantially their thermal resistance. This phenomenon is strengthened with an increase of the moisture content of the fabric. For the solution with 3% of salt, when the moisture content of fabrics reached respectively: 5%, the thermal conductivity (λ) of the fabrics increased almost by 15%, in case of 30% moisture content the thermal conductivity increase by about 25-30% and in case of 50% moisture content thermal conductivity increase 40 - 50% compared to thermal conductivity of wet fabric with the same moisture content but without salt.

Contrary to the above results, thermal conductivity of salty water in free state, according to the paper (13), decreases with increasing concentration of the solution and is lower than thermal conductivity of pure water. These results may seem quite enigmatic, as thermal conductivity of the solid salt is 6,5 W/m/K, i.e. much higher then thermal conductivity of pure water. On the other hand, the theory (13) indicates, that when the salty water penetrates into porous media, creates crystals, which results to the increase of the thermal conductivity of the wetted porous structures, which in our case can be the textile fabric.

Thus, the use of simulated sweat or salty water is recommended when testing comfort properties of wet fabrics, especially when the marine garments are designed.

4. CONCLUSIONS

From the presented results follows, that with increasing moisture content thermal insulation properties of the studied Nomex fabrics significantly decreased. This effect was caused by substituting of the air in pores by water with higher thermal conductivity than air, filling the hollow spaces inside dry porous fabrics. Also increasing percentage of the aqueous solutions of sodium chloride causes the increase of thermal conductivity of wetted fabrics and may reduce substantially their thermal resistance. Knowledge of these effects can be important when designing clothing for extreme climatic conditions and wearing of such clothing in harsh marine climate. This problem can by further complicated by the fact that water after simple drying without previous washing can crystallize in the fabric and seal the pores in fabrics, thus negatively affects not only the thermal insulation of clothing, but also the water vapor permeability of clothing. The effect of humidity on thermal insulation properties of the clothing during its wear should also depend on the used fibre materials, fabric finishing, clothing design etc. Continuing research in this area is necessary.

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