Damjana Celcar[1], Jelka Geršak[2], Harriet Meinander[3]
[1] Visoka šola za dizajn, Ljubljana
[2] Oddelek za tekstilne materiale in oblikovanje, Fakulteta za strojništvo, Univerza v Mariboru
[3] Fibre Materials Science, SmartWearLab, Tampere University of Technology, Finska

Evaluation of Textile Thermal Properties and their Combinations

Original Scientific Paper

Received *December 2009* • Accepted *February 2010*

Abstract

The paper presents the evaluation of textile material thermal properties and their combinations as used for business clothing systems, which was conducted through two separate studies. In the first study, an investigation of textile thermal properties was carried out using different measurement systems enabling the measuring of heat and/or moisture transmission through textile materials by using the hot-plate apparatus, the Thermo Labo II and the Permetest measurement systems. This part of the research investigated the correlations between the measured parameters of the textile thermal properties evaluated by using different measurement systems, and correlations between thickness and thermal properties. In the second study, the thermal properties of material combinations were evaluated by using a thermal sweating cylinder enabling the evaluation of heat and moisture transmission through textile materials or material combinations. The influences of different environmental conditions and sweating levels on the thermal properties of material combinations were investigated for this purpose.

Vodilni avtor/corresponding author:
Damjana Celcar
tel.: +386 5 923 50 06
e-mail: damjana.celcar@vsd.si

Vrednotenje toplotnih lastnosti tekstilij in njihovih kombinacij

Izvirni znanstveni članek

Poslano *december 2009* • Sprejeto *februar 2010*

Izvleček

V prispevku je predstavljeno vrednotenje toplotnih lastnosti ploskih tekstilij in njihovih kombinacij, namenjenih za poslovna oblačila, ki je potekalo v dveh delih. V prvem delu so bile raziskane toplotne lastnosti ploskih tekstilij ovrednotene na različnih merilnih napravah, ki omogočajo merjenje prehoda toplote in/ali prehoda vodne pare skozi plosko tekstilijo, in sicer s pomočjo toplotne plošče ter merilnih naprav Thermo Labo II in Permetest. V tem delu raziskave so bile raziskane povezave med lastnostmi ploskih tekstilij oziroma odvisnosti med posameznimi parametri toplotnih lastnosti analiziranih ploskih tekstilij, izmerjenimi na različnih merilnih napravah ter odvisnosti med toplotnimi lastnostmi in debelino tekstilije. V drugem delu raziskave so bile raziskane toplotne lastnosti kombinacij posameznih ploskih tekstilij in sicer s pomočjo toplotnega cilindra s simulacijo znojenja, ki omogoča merjenje prehoda toplote in prehoda vodne pare skozi tekstilije ali kombinacijo tekstilij. Za ta namen je bil raziskan vpliv klimatskih razmer in stopnje znojenja na toplotne lastnosti posameznih kombinacij ploskih tekstilij.
Raziskava je pokazala, da med parametri toplotnega upora, izmerjenega s toplotno ploščo, ter merilnima napravama Permetest in Thermo Labo II, obstajajo statistično pomembne korelacije, in da med toplotnim uporom, določenim iz kvocienta debeline in toplotne prevodnosti, dobljene z merilno napravo Thermo Labo II ter toplotnim uporom, dobljenim s toplotno ploščo in z merilno napravo Permetest prav tako obstaja korelacija. Potrjeno je, da se z naraščajočo debelino materiala vrednosti toplotnega upora in upora proti prehodu vodne pare ploskih tekstilij povečujejo. Hkrati je bilo ugotovljeno, da različne klimatske razmere in stopnje znojenja vplivajo na toplotne lastnosti kombinacij ploskih tekstilij. Ugotovljeno je bilo,

The results show that statistically significant correlations exist between the parameters of textile thermal resistances evaluated with different measurement systems using the hot-plate apparatus, the Thermo Labo II and the Permetest measurement systems. It is also evident from the results that by increasing textile thicknesses, the values of textile thermal resistances and water vapour resistance increase proportionally. The results of evaluating thermal properties of material combinations under different environmental and sweating conditions showed that different climate conditions and sweating levels influence the heat and moisture transmission properties of material combinations. The results show that dry and evaporative heat loss and water vapour transmission depend on climatic conditions or temperature gradient, respectively, between the cylinder surface and ambient temperature, and that different sweating levels influence the evaporative heat loss, corrected thermal resistance and water vapour transmission values.

Keywords: textiles, thermal properties, thermal comfort, hot plate, Thermo Labo II, Permetest, thermal sweating cylinder

1 Introduction

The thermal properties of clothing materials which display the ability of transporting heat and moisture from the human body surface into the environment are the dominant determinants of clothing thermal comfort. The metabolic heat and humidity produced by the human body, and the environmental parameters (i.e. air and radiant temperature, relative humidity and wind velocity) are also the parameters quantifying the clothing thermal comfort. Moreover, numerous other factors, e.g. colour, person's physical and psychological state, influence the transfer of energy and the feeling of comfort. In order to obtain good thermal comfort, there must be a balance between the heat production and heat dissipation [1, 2].

A variety of laboratory methods is available for determining the heat and moisture transmission properties of clothing materials. These laboratory tests are usually performed by using

da so toplotne lastnosti, tj. suhi in evaporativni toplotni tok ter sposobnost prehoda vodne pare odvisne od klimatskih razmer oziroma temperaturnega gradienta med površino cilindra in temperaturo zraka, in da se z različno stopnjo znojenja, vrednosti evaporativnega toplotnega toka, korigiranega toplotnega upora in sposobnosti prehoda vodne pare spremenijo.

Ključne besede: ploske tekstilije, toplotne lastnosti, toplotno udobje, toplotna plošča, Thermo Labo II, Permetest, toplotni cilinder s simulacijo znojenja

1 Uvod

Toplotne lastnosti ploskih tekstilij in iz njih izdelana oblačila, ki so namenjena zadrževanju toplote in prenosu vlage s površine človeškega telesa v okolico, so pomembne merske veličine toplotnega udobja pri nošenju oblačil. Na toplotno udobje pri nošenju oblačil pa razen toplotnih lastnosti vplivajo tudi klimatski parametri toplotnega okolja, tj. temperatura zraka in temperatura sevanja (okoliških površin) v okolju, relativna vlažnost zraka in hitrost gibanja zraka, kakor tudi proizvodnja toplote in vlage v telesu ter drugi parametri (barva, telesna in duševna aktivnost itd.). Za doseganje ustreznega toplotnega udobja pri nošenju oblačil mora torej obstajati dinamično ravnotežje med proizvedeno toploto in toploto, oddano v okolje [1, 2].

Za vrednotenje toplotnih lastnosti, tj. prehoda toplote in vlage skozi ploske tekstilije, obstajajo številne laboratorijske metode, ki večinoma omogočajo določanje samo ene lastnosti, ali toplotnega upora ali upora proti prehodu vodne pare skozi vzorec ploske tekstilije. Najbolj znana in najpogosteje uporabljena merilna naprava, ki omogoča merjenje prehoda toplote in vodne pare skozi površino ploske tekstilije v horizontalnem položaju, je toplotni model človeške kože ali t. i. kožni model [3]. Za določanje toplotnih lastnosti ploskih tekstilij je poleg kožnega modela uporabnih več merilnih naprav, ki so predmet številnih raziskav, saj so toplotne lastnosti pomembne veličine vrednotenja toplotnega udobja pri nošenju oblačil. Tako je v literaturi mogoče zaslediti prispevke, ki temeljijo na vrednotenju toplotnih lastnosti ploskih tekstilij in njihovih kombinacij [4–18].

V prispevku so predstavljeni izsledki raziskave vrednotenja toplotnih lastnosti ploskih tekstilij in njihovih kombinacij, namenjenih za moška poslovna oblačila, ki je potekala v dveh delih. V prvem delu raziskave so raziskane toplotne lastnosti ploskih tekstilij, ovrednotene s pomočjo toplotne plošče ter merilnima napravama Thermo Labo II in Permetest ter povezave med toplotnim uporom ploskih tekstilij, izmerjenim na omenjenih merilnih napravah. Hkrati je raziskana tudi odvisnost med toplotnim uporom in uporom proti prehodu vodne pare ter debelino tekstilije. V drugem delu so proučene toplotne lastnosti kombinacij uporabljenih ploskih tekstilij, ki simulirajo oblačilne sisteme poslovnih obla-

small pieces of fabric. Most of them require flat samples and are concerned with only one property, either the resistance to dry heat loss or water vapour transmission. The best known and commonly used physical test is the Hohenstein Skin Model [3], which allows the measurements of simultaneous dry and evaporative heat loss through horizontally-placed textile materials. A few other methods exist for testing the heat and/or moisture transmission through textile materials and have been of great interest to researchers, since thermal properties are among the major characteristics determining clothing thermal comfort. It is thus possible to find papers in the literature which focus on the evaluation of textile material thermal properties [4-18].

The research work presented in this paper summarizes the results of two separate studies concerned with the laboratory measurements of heat and water vapour transfer through clothing materials, and their combinations, as used for male business clothing. The first study presents the results of textile thermal properties evaluated by using the hot-plate apparatus, the Thermo Labo II and the Permetest measurement system. The correlations between the thermal properties measured using different test methods were evaluated in this part of the research, as well as the correlations between the thermal properties and thicknesses of the used fabrics. The second study presents the results for thermal properties of different clothing material combinations that simulate the male business clothing system. The combinations of clothing materials which simulate 4-layer and 6-layer clothing systems were defined upon the usability purpose of separate clothing layers in male business clothing system. The influences of different climatic conditions and sweating levels on the thermal properties of clothing material combinations were evaluated by using a thermal sweating cylinder.

2 The Evaluation of Textile Thermal Properties

The heat and water vapour transfer properties of textile materials are the dominant determinants for thermal comfort regarding the wearer and are essentially determined by the thermal

čil, ovrednotene s pomočjo toplotnega cilindra s simulacijo znojenja. Kombinacije uporabljenih tekstilij, ki simulirajo 4- in 6- slojni oblačilni sistem, so bile določene glede na namembnost posameznega sloja v oblačilnem sistemu moškega poslovnega oblačila. Za ta namen je bil raziskan vpliv klimatskih razmer in stopnje znojenja na toplotne lastnosti posameznih kombinacij ploskih tekstilij, ki simulirajo oblačilni sistem.

2 Vrednotenje toplotnih lastnosti tekstilij

Toplotne lastnosti ploskih tekstilij so pomembne veličine toplotnega udobja pri nošenju oblačil. Merski veličini, ki sta odraz teh sposobnosti, sta toplotni upor in upor tekstilij proti prehodu vodne pare [18]. Toplotni upor ploske tekstilije je veličina, ki pove, kako dobro tekstilija varuje pred čezmerno izgubo toplote, upor tekstilije proti prehodu vodne pare pa določa sposobnost tekstilije, da izpareli znoj oziroma vodno paro prenese s površine kože v okolje. To pomeni, da je v hladnem okolju najpomembnejša lastnost ustrezen toplotni upor, ki varuje pred izgubo toplote, v toplem okolju oziroma v razmerah, ko se znojenju ne moremo izogniti, pa postane pomemben dejavnik upor proti prehodu vodne pare. Ta dva parametra sta v procesu izmenjave toplote tudi edini veličini, na kateri lahko človek v veliki meri vpliva z izbiro pravilne kombinacije ploskih tekstilij, ki sestavljajo oblačilni sistem. Ali dana kombinacija tekstilij v oblačilnem sistemu podpira fiziološke funkcije organizma ali ne, je torej odvisno od njenih toplotnih lastnosti [19].

Proces izmenjave oziroma prenosa toplote skozi kombinacijo tekstilij, ki sestavljajo oblačilni sistem, v okolje je sestavljen iz procesa prenosa toplote s površine kože skozi oblačilo, ki je sestavljen iz suhega toplotnega toka ϕ_c, in evaporativnega (izparilnega, vlažnega) toplotnega toka ϕ_e [1, 12]. Količina suhe toplote, ki jo oddaja telo, je odvisna od razlike med srednjo temperaturo kože in temperaturo zraka, od velikosti površine oblačila, skozi katero prehaja toplota, ter od toplotnega upora oblačila. Čim večja je razlika med temperaturama, tem večji je suhi toplotni tok s površine kože v okolico. Fizikalno gledano je suhi toplotni tok količina toplote, ki jo telo v toplotnem stiku odda/sprejme v časovni enoti. Enači se z oddajanjem toplote, ki ga oddaja grelno telo pri sobni temperaturi. Grelno telo daje prav tako kot koža s prevajanjem toplote in konvekcije, kakor tudi s sevanjem, svojo toploto v okoliški zrak. Za suhi toplotni tok velja splošni izraz [1]:

$$\phi_c = \frac{(\bar{T}_s - T_a) \times A}{R_c} \quad (1)$$

kjer je:
ϕ_c – suhi toplotni tok [W],

and water vapour resistance [18]. The thermal resistance of a fabric represents a quantitative evaluation of how well the fabric provides a thermal barrier for the wearer. This means that the thermal resistance is an important parameter in cold environments, since it provides protection against thermal loss. The water vapour resistance of the fabric is a critical property for a clothing system, which must maintain the human body at the thermal equilibrium of the wearer. Clothing as an intermediate medium between the skin and the ambient conditions allows with the high water vapour permeability the human body to cool due to the evaporation. At high activity levels or in hot environments, the thermal resistance value alone is inadequate for characterizing and comparing clothing systems. The evaporation of sweat becomes an important avenue for heat loss. In addition, high water vapour permeability is of importance in cold environments, for it minimizes water accumulation in clothing, which leads to an increasing sense of discomfort. Therefore, both the thermal and water vapour resistances of fabrics are required in order to assess any heat exchange between the human body and the environment, and are related to human perceptions of comfort [19].

The process of heat transfer from the body into the environment through clothing materials is combined with heat transmission from the skin, which is considered to be the sum of the dry heat loss (ϕ_c) and the evaporative heat loss (ϕ_e) [1, 12]. The quantity of dry heat loss lost from the body depends on the difference between the mean skin temperature and ambient temperature of the clothing surface area, and the thermal resistance of the clothing. The greater the difference between the temperatures, the larger the dry heat loss from the skin into the environment. The dry heat loss is calculated with [1], equation 1, where:

ϕ_c – dry heat loss [W],
T_s – mean skin temperature [K],
T_a – ambient temperature [K],
A – surface area [m^2],
R_c – thermal resistance of textile material or clothing [m^{2}KW^{-1}].

As shown schematically in Figure 1, the total thermal resistance ($R_{c,total}$) of a single textile ma-

$\bar{T}_s$ – srednja temperatura kože [K],
T_a – temperatura zraka v okolici [K],
A – površina, skozi katero prehaja toplota [m^2],
R_c – toplotni upor tekstilije oziroma oblačila [m^2 KW^{-1}].

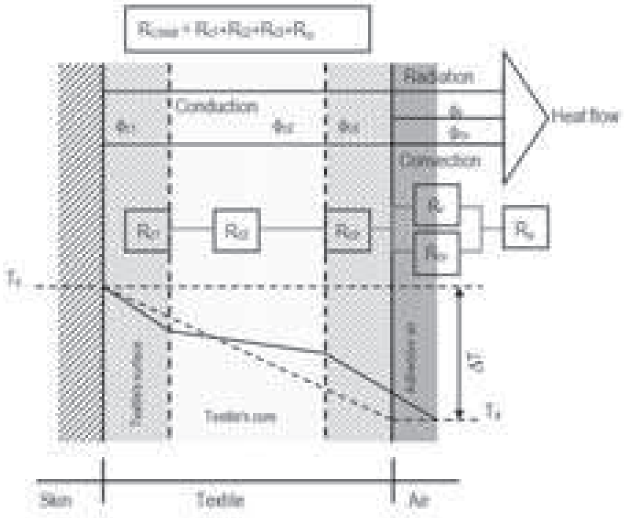


Figure 1: Schematic representation of dry heat transmission through one layer of textile material [18]

Iz slike 1 je videti, da je skupni toplotni upor tekstilije, ki je v stiku s površino kože, seštevek različnih komponent vseh procesov, s katerimi se prenaša toplota s površine telesa skozi oblačilo v okolico (kondukcija ali prevajanje toplote, konvekcija in sevanje ali radiacija) [18]. V vročem in suhem okolju je najpomembnejši termoregulacijski proces izločanje znoja, pri čemer se poveča parni tlak na površini kože in s tem poraba toplote za izhlapevanje znoja. Znoj, ki izhlapeva na površini kože, potuje od kože skozi oblačilo v okoliški zrak zaradi razlike tlaka vodne pare na površini kože (p_s) in tlaka vodne pare v okoliškem zraku (p_a). Evaporativni toplotni tok ϕ_e, ki je odvisen od velikosti površine, skozi katero prehaja toplotni tok, razlike tlakov ($p_s - p_a$) in toplotnega upora oblačila proti prehodu vodne pare, je podan z izrazom [1]:

$$\phi_e = \frac{(\bar{p}_s - p_a) \times A}{R_e} \qquad (2)$$

kjer je:
ϕ_e – evaporativni toplotni tok [W],
$\bar{p}_s$ – srednji parcialni tlak vodne pare na površini kože [Pa],
p_a – parcialni tlak vodne pare v okoliškem zraku [Pa],
A – površina, skozi katero prehaja evaporativni toplotni tok [m^2],
R_e – upor tekstilije oziroma oblačila proti prehodu vodne pare [Pa m^{2}W^{-1}].

Vrednotenje toplotnih lastnosti ploskih tekstilij se izvaja na različnih merilnih napravah, ki simulirajo prehod toplote in/ali vo-

terial which is in direct contact with the skin is made up of different components relating to physical mechanisms (i.e. conduction, convection and radiation) [18]. The most important thermoregulation process in hot and dry environments is the evaporation of sweat, where water vapour pressure increases on the skin surface and thus causes evaporative heat losses. Due to the differences in water vapour pressure on the skin surface (p_s) and in the environment (p_a), the sweat evaporates from the skin surface and diffuses through the clothing into the environment as water vapour. The evaporative heat loss (φ_e) depends on the surface area, water vapour pressure difference ($p_s - p_a$) and water vapour resistance of the clothing material, and is calculated with [1], equation 2, where:

ϕ_e – evaporative heat loss [W],

$\overline{p_s}$ – mean water vapour pressure on skin [Pa],

p_a – water vapour pressure of ambient [Pa],

A – surface area [m²],

R_e – water vapour resistance of textile material or clothing [Pa×m²W⁻¹].

There are several testing methods for estimating the thermal properties of textile materials. For physical tests, a device is used for simulating the skin heat and/or water vapour production and can be performed either on textile materials or completed clothing systems. Most tests are concerned with only one property, i.e. the resistance to dry heat loss or to water vapour transmission. The commonly used physical test is a standard testing method using a sweating guarded hot-plate instrument (Hautmodell, Skin model) [3, 19], which enables the measurements of simultaneous dry and evaporative heat loss through horizontally-placed textile materials. Some of the other methods for testing the heat and/or moisture transmission through textile materials are:

- *thermal sweating cylinder that enables the evaluation of thermal resistance, corrected thermal resistance, and heat and water vapour transmission through textile materials or material combinations [12],*
- *Thermo Labo II measurement system that enables the evaluation of the following textile thermal properties: warm-cool feeling, thermal conductivity, thermal resistance, water vapour resistance and heat-keeping property [21],*

dne pare skozi ploske tekstilije. Večina naprav omogoča določanje samo ene lastnosti, ali toplotnega upora ali upora proti prehodu vodne pare. Za merjenje toplotnih lastnosti ploskih tekstilij se najpogosteje uporablja t. i. kožni model (nem. *Hautmodell,* angl. *Skin model*) [3, 19], ki omogoča merjenje prehoda toplote in prehoda vodne pare skozi površino ploske tekstilije. Poleg t. i. kožnega modela se za vrednotenje toplotnih lastnosti ploskih tekstilij uporabljajo še naslednje merilne naprave:

- toplotni cilinder s simulacijo znojenja (angl. *Thermal sweating cylinder*), ki omogoča določanje toplotnega upora, korigiranega toplotnega upora, evaporativnega toplotnega toka in sposobnosti prehoda vodne pare skozi plosko tekstilijo ali kombinacijo tekstilij [12];
- merilna naprava Thermo Labo II, ki omogoča določanje toplotnih lastnosti ploskih tekstilij, kot so: t. i. toplo-hladen občutek (angl. *Warm-cool feeling*), toplotna prevodnost, toplotni upor, upor proti prehodu vodne pare in koeficient ohranjanja toplote [21];
- toplotna plošča (angl. *Guarded hot plate apparatus*), ki omogoča določanje toplotnega upora in toplotne prevodnosti ploskih tekstilij ali kombinacij tekstilij [22];
- merilna naprava Alambeta, ki omogoča določanje toplotnih lastnosti ploskih tekstilij, kot so: t. i. toplo-hladen občutek, toplotni upor, toplotna prevodnost, toplotna vpojnost in vpojnost vodne pare [8]; in
- merilna naprava Permetest, ki omogoča določanje toplotnega upora in upora proti prehodu vodne pare ploskih tekstilij ali oblačil [20] itd.

3 Eksperimentalni del

Raziskava toplotnih lastnosti ploskih tekstilij in njihovih kombinacij je bila razdeljena na dva dela. Prvi je temeljil na raziskavah toplotnih lastnosti tekstilij, ovrednotenih na različnih merilnih napravah, ter raziskavi ostalih splošnih lastnosti desetih različnih tekstilij, namenjenih za moška poslovna oblačila, ki so bile določene v standardnih razmerah testiranja po zahtevah standardov, kot so:

- debelina ploskih tekstilij (*h*) po zahtevah standarda ISO 5084: 1996 [23] in masa (W) po ISO 3801: 1977 [24],
- zračna prepustnost (Q_{air}) po zahtevah standarda ISO 9237: 1995 [25],
- toplotni upor (R_{ct}) in toplotna prevodnost (λ), določena s toplotno ploščo po zahtevah standarda ISO 5085-1:1989 [22],
- upor proti prehodu vodne pare (R_{et}) in toplotni upor (R_{ct}), določena s pomočjo naprave Permetest [20],
- toplotni upor tekstilije (R_{ct}), toplo-hladni občutek (q_{max}), toplotna prevodnost (λ) ter koeficient sposobnosti ohranjanja toplote (α) so bile določene s pomočjo merilnega sistema Thermo Labo II [21],

- *guarded hot-plate apparatus that enables the evaluation of thermal resistance and thermal conductivity of textile materials [22],*
- *Alambeta measurement system that enables the evaluation of the following thermal properties: warm-cool feeling, thermal resistance, thermal conductivity, thermal absorptiveness and moisture absorptiveness [8], and*
- *Permetest measurement system that enables the evaluation of thermal resistance and the water vapour resistance of textile materials or clothing [20].*

3 Experimental

The experimental part of this research work was divided into two studies. The first study of the experimental work included the investigations of textile thermal properties evaluated with different measurement systems and the investigations of the basic properties of textiles used in male business clothing. Table 1 shows a review

– prepustnost vodne pare (*WVT*), določena po metodi Gore & Associates, Inc. [7], modificirani po ameriškem standardu ASTM E96-66.

V preglednici 1 so podani rezultati splošnih lastnosti uporabljenih tekstilij, ki so deloma objavljeni v Celcar et.al. [26].

Table 1: Description of test materials and their basic properties

Fabric sample	Clothing system layer	Fabric content	Weight	Thickness	Air permeability
			W/gm^{-2}	$h^{1)}$/mm	Q_{air}/lm^{-2}s^{-1}
TK01	Male suit	100% WO	179.0	0.51	323.5
TK02	Male suit	88% WO, 12% PA	206.0	0.49	75.2
TK03	Male suit	98% WO, 2% EL	189.0	0.49	223.0
TK07	Shirt	78% CO, 22% PES	85.0	0.21	322.0
TK09	Coat	100% WS	300.0	1.71	196.5
TK12	Suit liner	100% CV	76.0	0.11	596.0
TK14	Coat liner	100% CV	101.0	0.14	125.2
TK15	Underwear	100% CO	221.0	1.59	618.0
TK21	Suit liner	1st layer: 100% CV, 2nd layer: Outlast®: Acryil with PCMs	93.0	0.21	151.0
TK22	Male suit	68% Outlast®: Acryil with PCMs, 28% WO, 4% EL	168.0	0.49	277.0

1) Thickness at pressure 0.069 gfcm^{-2} (1 gf = 0.9807 cN ≈ 1 cN)

Drugi del je temeljil na raziskavah toplotnih lastnosti kombinacij, v prvem delu raziskave uporabljenih ploskih tekstilij, ki simulirajo oblačilni sistem. Za ta namen je bilo določenih 16 različnih kombinacij ploskih tekstilij (preglednica 2), ki so bile ovrednotene s pomočjo toplotnega cilindra s simulacijo znojenja, in sicer pri treh različnih temperaturah zraka (25 °C, 10 °C in –5 °C) in dveh stopnjah znojenja (100 in 200 gm^{-2}h^{-1}). Kombinacije uporabljenih ploskih tekstilij, ki simulirajo 4- in 6-slojni oblačilni sistem, so bile določene glede na namembnost posameznega sloja v oblačilnem sistemu moškega poslovnega oblačila. Osem kombinacij ploskih tekstilij, ki simulirajo 4-slojni oblačilni sistem (kombinacije z oznako c1 do c8), je bilo sestavljenih iz tekstilije za spodnje perilo, moško srajco in podloženo moško obleko (sestavljeno iz spodnjega sloja – podloge in vrhnjega sloja – tkanine za moško obleko). Te raziskave so bile izvedene v toplem in hladnem okolju pri dveh klimatskih pogojih in dveh stopnjah znojenja (100 in 200 gm^{-2}h^{-1}), in *of the selected materials and their basic properties, which are partly published in Celcar et al [26]. The determinations of basic material, thermal and water vapour transmission properties in steady-state conditions were conducted according to the standardized test methods, as follows:*

- *material thickness (h) according to ISO 5084:1996 [23] and mass per unit area of textile materials (W) according to ISO 3801:1977 [24];*
- *air permeability (Q_{air}) of textile materials according to ISO 9237: 1995 [25];*
- *thermal resistance (R_{ct}) and thermal conductivity (λ) of textile materials determined with a hot-plate apparatus according to ISO 5085-1:1989 [22];*
- *water vapour resistance (R_{et}) and thermal resistance (R_{ct}) determined with Permetest measurement [20];*
- *thermal resistance (R_{ct}), warm-cool feeling (q_{max}), thermal conductivity (λ) and heat-keeping properties (α) determined with the Thermo Labo II measurement system [21];*
- *water vapour transmission (WVT) of textile materials according to the Gore cup method modified by Gore-Tex [7].*

sicer pri temperaturi zraka 25 °C in 10 °C ter 65-odstotni relativni zračni vlažnosti in hitrosti gibanja zraka 0,1 ms^{-1}. Preostalih osem kombinacij ploskih tekstilij (kombinacije z oznako c9 do c16), ki simulirajo 6-slojni oblačilni sistem, je bilo sestavljenih iz tekstilije za spodnje perilo, moško srajco in podloženo moško obleko (sestavljeno iz spodnjega sloja – podloge in vrhnjega sloja – tkanine za moško obleko) ter tekstilije za moški podložen plašč (sestavljen iz spodnjega sloja – podloge in vrhnjega sloja – tkanine za moški plašč). Raziskave 6-slojnih oblačilnih sistemov so bile izvedene v hladnem in mrzlem okolju pri dveh klimatskih pogojih in dveh stopnjah znojenja (100 in 200 $gm^{-2}h^{-1}$), in sicer pri temperaturi zraka 10 °C in 65-odstotni relativni zračni vlažnosti ter pri temperaturi zraka –5 °C in hitrosti gibanja zraka 0,1 ms^{-1}. Za natančnost meritev sta bili izvedeni dve meritvi, pri 5-odstotnem odstopanju, pa še dodatno ena oziroma dve za analizo ponovljivosti meritev. Pri vseh 16 kombinacijah ploskih tekstilij, ki so simulirale oblačilni sistem, je bil za spodnje perilo ter moško srajco uporabljen enak material.

Table 2: Tested material combinations

Clothing layer	Fabric sample	Combinations															
		c1	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12	c13	c14	c15	c16
Underwear	TK15	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Shirt	TK07	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Liner	TK12	*	*	*	*					*	*	*	*				
	TK21					*	*	*	*					*	*	*	*
Male suit	TK01	*				*				*				*			
	TK02		*				*				*				*		
	TK03			*				*				*				*	
	TK22				*				*				*				*
Male coat	TK09									*	*	*	*	*	*	*	*
Coat liner	TK14									*	*	*	*	*	*	*	*

3.1 Testne metode – uporabljeni merilni sistemi in metode

Raziskava toplotnih lastnosti analiziranih ploskih tekstilij je bila izvedena s pomočjo treh različnih merilnih sistemov in po metodi Gore & Associates, Inc. Pregled in primerjava uporabljenih merilnih sistemov ter metod za določanje toplotnih lastnosti ploskih tekstilij sta podana v preglednici 3.

Za vrednotenje toplotnih lastnosti kombinacij ploskih tekstilij, ki sestavljajo oblačilni sistem, je bil uporabljen toplotni cilinder s

Table 3: Comparison between measurement systems and methods for evaluating thermal properties of textile materials (continued overleaf).

Measuring system/ method	Hot plate apparatus [22]	Thermo Labo II [21]	Permetest [20]	Gore & Associates, Inc. method [7]
Measured/ calculated parameters	– thermal resistance R_{ct} [m^{2}KW^{-1}] – thermal conductivity λ [Wm^{-1}K^{-1}]	– warm-cool feeling q_{max} [Wcm^{-2}] – thermal conductivity λ [Wm^{-1}K^{-1}] – heat-keeping property α [%] – thermal resistance R_{ct} [m^{2}KW^{-1}] – water-vapour resistance R_{et} [Pa·m^{2}W^{-1}]	– thermal resistance R_{ct} [m^{2}KW^{-1}] – water vapour resistance R_{et} [Pa·m^{2}W^{-1}]	– water vapour transmission *WVT* [gm^{-2}h^{-1} 24h]
Methods	The method is based on measuring temperatures with three temperature sensors (T_1, T_2 and T_3). The thermal resistance of textiles is calculated from measured temperature values.	The method is based on measuring heat flow through sample (ϕ). The thermal conductivity and thermal resistance by conduction are calculated from measured heat flow. For evaluating the heat-retaining property and thermal resistance of textile in wind tunnel, two methods are used: dry contact method (SK), where sample is in direct contact with hot plate, and dry non-contact method (SBK), where constant distance space exists between sample and hot plate. The same procedure with wet filter paper on the heat plate is used for evaluating water vapour resistance. Warm-cool feeling (q_{max}) is recorded as maximum level of heat flow required per unit area [Wcm^{-2}].	The method is based on measuring heat flow through sample (ϕ_{ct}) and without sample (ϕ_0). The thermal resistance of textiles is calculated from measured heat flow values. For evaluating water vapour resistance of textiles, distilled water with detergent is dosed with syringe into the measuring heat, and heat flow through sample (ϕ_{et}) and without sample (ϕ_0) are measured.	The method is based on measuring weight changes of sample before (G_0) and after time interval (G_t). The sample is strained over a small dish with solid dry agent. The container with sample and dry agent is vertically placed on the Gore-Tex seal laminate, swimming on water in measuring dish. From measured weight changes, the water vapour transmission of the textile is calculated.
Measuring conditions	Ambient temperature T_a = 20 ± 2 °C and relative humidity RH = 65 ± 2%.			

Table 3: Comparison between measurement systems and methods for evaluating thermal properties of textile materials (continued overleaf).

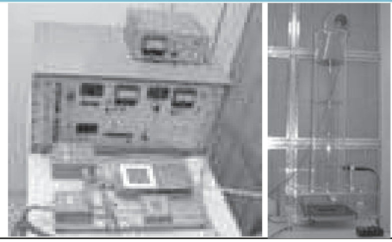
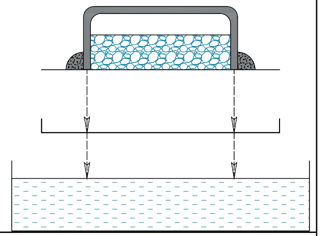
Measuring system/ method	Hot plate apparatus [22]	Thermo Labo II [21]	Permetest [20]	Gore & Associates, Inc. method [7]
Measuring device/system				
Calculation and expression of results	$R_{ct}=\left[R_s\cdot\left(\frac{T_2-T_3}{T_1-T_2}\right)\right]-R_{ct0}$ $R_{ct0}=R_s\cdot\left(\frac{T_2'-T_3'}{T_1'-T_2'}\right)$ $\lambda=\frac{h}{R_{ct}}$	$\lambda=\frac{\phi\cdot h}{A\cdot\Delta T}$ $R_\lambda=\frac{h}{\lambda}$ $\alpha=\frac{\phi_0-\phi_{ct}}{\phi_0}$ $\alpha_{SK}=\frac{\phi_0-\phi_{ct-SK}}{\phi_0}$ $\alpha_{SBK}=\frac{\phi_0-\phi_{ct-SBK}}{\phi_0}$ $R_{ct}=\frac{(T_s-T_a)\cdot A}{\phi_{ct}}$ $R_{et}=\frac{(p_s-p_a)\cdot A}{\phi_{et}}$ $R_{ct-SK}=\frac{(T_s-T_a)\cdot A}{\phi_{ct-SK}}$ $R_{ct-SBK}=\frac{(T_s-T_a)\cdot A}{\phi_{ct-SBK}}$	$R_{ct}=K\cdot(T_h-T_a)\cdot\left(\frac{1}{\phi_{ct}}-\frac{1}{\phi_0}\right)$ $R_{et}=(p_s-p_a)\cdot\left(\frac{1}{\phi_0}-\frac{1}{\phi_{ct}}\right)=$ $=C\cdot(100-RH)\cdot\left(\frac{1}{\phi_{ct}}-\frac{1}{\phi_0}\right)$	$WVT=\frac{G_t-G_0}{A\cdot t}\cdot 24h$
Parameters	R_{ct0} – thermal resistance of the apparatus without sample [m^{2}KW^{-1}], R_s – thermal resistance of plate [0.072 m^{2}KW^{-1}], T_1 – temperature registered with T_1 without sample [K],	λ – thermal conductivity [Wm^{-1}K^{-1}], A – area of BT-heat plate [A = 0.0025 m^2], h – thickness of sample [m], ΔT – temperature gradient ($T_{BT}-T_a$) [K], ϕ – heat flow [W], T_{BT} – temperature of BT box [K], T_a – air temperature [K], α – heat-keeping property [%],	ϕ_{ct} – heat flow with sample [Wm^{-2}], ϕ_0 – heat flow without sample [Wm^{-2}], T_h – temperature of heat plate in measuring head [K], T_a – air temperature [K],	G_0 – weight of dish with sample before testing [g], G_t – weight of dish with sample after 4-hour testing [g], t – time interval (t = 4h) [h], A – test area (A = 12.6 cm^2) [m^2].

Table 3: Comparison between measurement systems and methods for evaluating thermal properties of textile materials

Measuring system/ method	Hot plate apparatus [22]	Thermo Labo II [21]	Permetest [20]	Gore & Associates, Inc. method [7]
Parameters	$T_{2'}$ – temperature registered with T_2 without sample [K], $T_{3'}$ – temperature registered with T_3 without sample [K] T_1 – temperature registered with T_1 with sample [K], T_2 – temperature registered with T_2 with sample [K], T_3 – temperature registered with T_3 with sample [K], h – thickness of sample at pressure 6.9 Pa (0.069 $cNcm^{-2}$) [m], R_{ct} – thermal resistance of textile materials [m^2KW^{-1}], λ – thermal conductivity [$Wm^{-1}K^{-1}$]	ϕ_{ct} – heat flow with sample [W], ϕ_0 – heat flow without sample [W], α_{SK} – heat-keeping property evaluated with dry contact method [%], α_{SBK} – heat-keeping property evaluated with dry non-contact method [%], ϕ_{ct-SK} – heat flow with sample measured with dry contact method [W], ϕ_{ct-SBK} – heat flow with sample measured with dry non-contact method [W], R_{ct} – thermal resistance of textile materials [m^2KW^{-1}], R_{ct-SK} – thermal resistance evaluated with dry contact method [m^2KW^{-1}], R_{ct-SBK} – thermal resistance evaluated with dry non-contact method [m^2KW^{-1}], ϕ_{ct-SK} – heat flow measured with dry contact method [W], ϕ_{ct-SBK} – heat flow measured with dry non-contact method [W], ϕ_{ct} – dry heat flow [W], T_s – main temperature of BT heat plate (skin temperature) [K], ϕ_{et} – heat loss by evaporation of water [W], p_s – saturated vapour pressure on the BT-plate [Pa], p_a – vapour pressure in the tunnel [Pa], R_λ – thermal resistance by conduction [m^2KW^{-1}].	K – calibration constant of standard sample with known R_{ct}, RH – relative humidity in tunnel [%], p_s – saturated vapour pressure in air [Pa], p_a – vapour pressure in the tunnel [Pa], C – calibration constant of standard sample with known R_{et}	

The second study of the experimental work included the testing of different combinations of textile materials used in the first part of research, which simulated business clothing systems. 16 different combinations of materials (cf. Table 2) were chosen for testing on the thermal sweating cylinder at three different environmental temperatures (i.e. 25 °C, 10 °C and −5 °C) and two sweating conditions (100 and 200 $gm^{-2}h^{-1}$).

The combinations of clothing materials which simulate the 4-layer and the 6-layer clothing systems were defined through the purpose of usability of separate clothing layers in male business clothing systems. The eight tested combinations of materials, which simulate the 4-layer business clothing system (c1−c8), consisted of underwear layer, shirt layer, liner layer for suits and outerwear-suit layer. All tests were performed under two warm-cool environmental conditions (10 °C/65% and 25 °C/65%, air velocity 0.1 ms^{-1}) and at two sweating levels (100 and 200 $gm^{-2}h$). The other eight combinations of materials, which simulated the 6-layer business clothing system (c9−c16), consisted of underwear layer, shirt layer, liner layer for suits, outerwear-suit layer, liner layer for coats and outerwear-layer for coats. The tests in a cool-cold environment were conducted under two environmental conditions (10 °C/65% and −5 °C, air velocity 0.1 ms^{-1}) at two sweating levels (100 and 200 $gm^{-2}h$). The same textile materials for underwear, shirt, liner for suits and coats were used for testing and two parallel tests were carried out for all material combinations. If the difference in results was > 5%, a third test was done, whereby the two with most comparable results were retained and the one with the highest deviation was ignored.

3.1 Test Methods

The research of textile thermal properties was performed by using three different measurement systems and the Gore & Associates, Inc. method. A review and comparison of the used measurement systems and methods for measuring the thermal properties of textile materials are shown in Table 3.

A thermal sweating cylinder was constructed to measure the simultaneous transmission of heat

simulacijo znojenja (angl. *Thermal sweating cylinder*), slika 2, ki simulira prehod toplote skozi tekstilijo ali kombinacijo tekstilij, kakor tudi prehod vodne pare s pomočjo številnih simuliranih žlez znojnic, ki so na površini cilindra in oskrbujejo oziroma dovajajo določeno količino vode na površino. Omogoča merjenje toplotnega upora, korigiranega toplotnega upora, ki pomeni upor kombinacije tekstilij pri znojenju in sposobnost prehoda vodne pare skozi ploske tekstilije ali kombinacijo tekstilij pri različnih klimatskih razmerah in stopnjah znojenja. Deluje podobno kot kožni model, le da so meritve izvedene v obliki cilindra ali trupa telesa, pri toplotni plošči ali kožnem modelu pa je preizkušanec vstavljen horizontalno [12, 26]. Meritve se lahko izvajajo pri različnih klimatskih razmerah v klimatski komori (temperaturno območje od −50 °C do +70 °C, relativna vlažnost zraka od 15- do 95-odstotna), kjer je cilinder postavljen na tehtnico, ki med merjenjem zaznava spremembe v masi cilindra s preizkušancem.

Figure 2: Thermal sweating cylinder dressed with a combination of materials

Stena cilindra je ogrevana na temperaturo, ki ustreza temperaturi kože (35 °C). Voda se po cevkah dovaja do površine cilindra oziroma do simuliranih žlez znojnic z računalniško nadzorovanim črpalnim sistemom, kjer izhlapeva in prehaja skozi površino v obliki vodne pare. Sistem omogoča nadzor dovoda vode za vsako posamezno žlezo znojnico in nastavitev količine dovedene vode v določenih mejah (od 0 do največ 300 $gm^{-2}h^{-1}$ za merjenje brez preizkušanca pri normalni temperaturi prostora), ki so odvisne od preizkušanca in pogojev merjenja. Količina absorbirane vode v posameznem sloju tekstilije se določi s tehtanjem posameznih slojev preizkušanca pred merjenjem in takoj po merjenju. Za nadzor *and moisture through clothing materials or material combinations. Measurements using the cylinder were made three-dimensionally and by using this method, it is possible to test different types of materials or material combinations under different climate conditions in the climate chamber. The basic idea is that the cylinder produces heat and moisture similarly to the human body. The cylinder is dressed with the test material or a combination of materials (cf. Figure 2) and placed into the climate chamber (temperature range between −50 °C and +70 °C, relative humidity between 15% and 95%) on a balance, which records any weight changes during the test. The cylinder wall is heated to the surface temperature corresponding to skin temperature (35 °C). A predetermined amount of liquid water is supplied to the surface (to the sweat gland), where it evaporates and leaves the cylinder as water vapour. The amount of water supply can be chosen within certain limits (from 0 to the maximum value within normal room temperature and without test material, approx. 300 gm^{-2}h^{-1}). The amount of water condensed in the textiles is determined by weighing the samples prior to and immediately after the test [12, 26].*

A computer program is used during the test for the control and measurement of the cylinder surface temperature (°C), heat supply (Wm^{-2}), temperatures at different points (layers of materials, °C), total weight increase during the test (g) and weight increases of individual material layers (g). Based on the measured values, the total thermal resistances of the combinations of textile materials ($R_{ct,tot}$), which includes thermal resistance of the boundary air layer, is calculated with [12], equation 3, where:

$R_{ct,tot}$ – total thermal resistance of the combination of materials [m^{2}KW^{-1}],

T_c – cylinder surface temperature [K],

T_a – ambient temperature in climate chamber [K],

A – surface test area [A = 0.29 m^2],

ϕ_c – heat supplied to the cylinder in the dry test [W].

Taking into account that the heat supply is partly used to evaporate the water, the corrected thermal resistance ($R_{ct,corr}$) value is calculated with [12] equation 4, where ϕ_{sw} means heat sup-

temperature in zajemanje podatkov skrbi računalnik, s katerim je mogoče med merjenjem spremljati poleg sprememb temperature na površini cilindra (°C) še količino dovedene toplote (toplotna moč, ki greje površino cilindra na želeno temperaturo, v Wm^{-2}) in temperaturo posameznih slojev materiala (°C) [12, 26]. Na podlagi izmerjenih vrednosti se izračuna toplotni upor celotne kombinacije ploskih tekstilij z zračnim slojem med tekstilijami, ki je izražen kot skupni toplotni upor ($R_{ct,tot}$) z izrazom [12]:

$$Rct_{tot} = \frac{T_c - T_a}{\phi_c} \times A \tag{3}$$

kjer je:

Rct_{tot} – skupni toplotni upor kombinacije ploskih tekstilij [m^{2}KW^{-1}],

T_c – srednja temperatura na površini cilindra [K],

T_a – temperatura zraka v klimatski komori [K],

A – površina območja testiranja na cilindru [A = 0,29 m^2],

ϕ_c – količina dovedene toplote oziroma suhi toplotni tok [W].

Dovod toplote je med znojenjem delno uporaben za evaporacijo vode, tako da je t. i. korigirani toplotni upor ploske tekstilije ali kombinacije tekstilij ($R_{ct,corr}$) izražen takole [12]:

$$Rct_{corr} = \frac{T_c - T_a}{\phi_{sw} - \phi_e} \times A \tag{4}$$

ϕ_{sw} – količina dovedene toplote pri znojenju oziroma toplotni tok pri znojenju [W].

Pri tem je evaporativni toplotni tok definiran z izrazom [12]:

$$\phi_e = (m_i - m_c) \times \varphi_{25\,°C} = m_e \times \varphi_{25\,°C} \tag{5}$$

kjer je:

Rct_{corr} – korigirani toplotni upor kombinacije ploskih tekstilij [m^{2}KW^{-1}],

ϕ_e – evaporativni toplotni tok [W],

m_i – količina dovedene vode v cilinder [gh^{-1}],

m_c – količina absorbirane vodne pare v slojih tekstilij [gh^{-1}],

m_e – količina evaporirane vodne pare [gh^{-1}],

$\varphi_{25°C}$ – specifična toplota evaporacije vode pri 25 ºC = 0,684 Whg^{-1}.

Odnos med količino evaporirane vodne pare (m_e) in količino dovedene vode v cilinder (m_i) je izražen kot sposobnost prehoda vodne pare skozi plosko tekstilijo in je podan z izrazom [12]:

$$M_e = \frac{m_e}{m_i} \times 100 \tag{6}$$

kjer je:

plied to the cylinder in the wet test (W). Evaporative heat loss is calculated with [12] equation 5, where:

$R_{ct,corr}$ – corrected thermal resistance of the combination of materials [m^2KW^{-1}],

ϕ_e – evaporative heat loss [W],

m_i – amount of water fed into the cylinder [gh^{-1}],

m_c – amount of condensed water in the textile materials [gh^{-1}],

m_e – amount of evaporated water [gh^{-1}],

$\varphi_{25°C}$ – specific heat of evaporated water at 25 °C = 0.684 Whg^{-1}.

The amount of evaporated water (M_e) as the percentage of water input gives the value of the water vapour transmission of the tested material combination. The amount of evaporated water is calculated with [12] equation 6, where:

M_e – water vapour transmission in %.

4 Results and Discussion

The results of the performed research work are presented as:

– the results for the thermal properties of clothing materials evaluated by using different

M_e – sposobnost prehoda vodne pare skozi tekstilijo ali kombinacijo tekstilij, izražena v %.

4 Rezultati z razpravo

Rezultati raziskave toplotnih lastnosti ploskih tekstilij in njihovih kombinacij so v nadaljevanju podani kot:

- rezultati toplotnih lastnosti ploskih tekstilij, ovrednoteni z različnimi merilnimi sistemi: v preglednici 4 so podani rezultati, dobljeni s pomočjo toplotne plošče, merilnega sistema Permetest in metode Gore & Associates, Inc., medtem ko so v preglednici 5 podani rezultati, dobljeni s pomočjo merilnega sistema Thermo Labo II;
- rezultati medsebojnih povezav oziroma odvisnosti med toplotnimi lastnostmi, ovrednotenimi z različnimi merilnimi sistemi, ter rezultati odvisnosti med toplotnimi lastnostmi in debelino ploskih tekstilij; in
- rezultati toplotnih lastnosti kombinacij ploskih tekstilij, določeni s pomočjo toplotnega cilindra s simulacijo znojenja, kot so: suhi toplotni tok oziroma izguba suhe toplote ter toplotni tok pri znojenju, toplotni upor in korigirani toplotni upor ter sposobnost prehoda vodne pare.

Deloma so rezultati toplotnih lastnosti, izmerjenih s pomočjo toplotne plošče in po metodi Gore & Associates, Inc. (preglednica 4) ter rezultati na slikah 6a, 7a in 7c ter 8b objavljeni v Celcar et.al.

Table 4: Thermal and water vapour transmission properties of clothing materials, evaluated with the hot-plate apparatus, Permetest measurement system and Gore & Associates, Inc. method

Fabric sample	Thermal resistance		Thermal conductivity	Water vapour transmission	Water vapour resistance
	R_{ct} / m^2KW^{-1}		λ / $Wm^{-1}K^{-1}$	WVT /$gm^{-2}24h^{-1}$	R_{et} / m^2PaW^{-1}
	Hot plate	Permetest	Hot plate	Gore & Associates, Inc.	Permetest
TK 01	0.016	0.015	0.032	5695	0.994
TK 02	0.011	0.012	0.045	5552	1.118
TK 03	0.011	0.010	0.045	5648	0.795
TK 07	0.005	0.006	0.042	5713	0.451
TK 09	0.053	0.067	0.032	4520	1.972
TK 12	0.001	0.003	0.110	6008	0.198
TK 14	0.002	0.005	0.070	5804	0.646
TK 15	0.036	0.037	0.044	5256	2.340
TK 21	0.002	0.003	0.105	5368	0.474
TK 22	0.014	0.011	0.035	5306	0.842

Table 5: Thermal properties of clothing materials, evaluated with the Thermo Labo II measurement system

Fabric sample	Thickness $h^{2)}$	Warm-cool feeling q_{max}	Heat flow ϕ	Thermal conductivity λ	Thermal resistance by conduction / R_{λ}	R_{ct} Thermal resistance		Heat-keeping property / α	
						$R_{ct\text{-}SK}$	$R_{ct\text{-}SBK}$	α_{SK}	α_{SBK}
	[mm]	[Wcm^{-2}]	[W]	[$Wm^{-1}K^{-1}$]	[m^2KW^{-1}]	[m^2KW^{-1}]	[m^2KW^{-1}]	[%]	[%]
TK 01	0.430	0.202	3.12	0.044	0.0097	0.019	0.044	31.8	60.3
TK 02	0.428	0.225	3.48	0.049	0.0087	0.019	0.044	28.3	60.8
TK 03	0.433	0.220	3.36	0.050	0.0087	0.018	0.044	26.4	60.5
TK 07	0.197	0.304	5.93	0.041	0.0048	0.022	0.042	42.1	59.7
TK 09	1.210	0.117	1.15	0.044	0.0272	0.026	0.049	47.9	64.7
TK 12	0.119	0.394	7.51	0.033	0.0036	0.018	0.039	28.3	56.7
TK 14	0.147	0.352	4.70	0.024	0.0061	0.019	0.044	28.7	60.0
TK 15	1.037	0.167	1.89	0.063	0.0164	0.022	0.045	40.8	63.0
TK 21	0.225	0.366	4.57	0.035	0.0064	0.017	0.043	24.4	60.3
TK 22	0.413	0.231	3.48	0.049	0.0085	0.018	0.044	25.9	60.7

2) Thickness at pressure 6.0 $gfcm^{-2}$
SK – dry contact method
SBK – dry non-contact method

measurement systems: Table 4 presents the results evaluated with the hot-plate apparatus, Permetest measurement system, and the Gore & Associates, Inc. method, while Table 5 shows the results evaluated by using the Thermo Labo II measurement system;

- *the results of correlations between textile thermal properties measured by using different test methods, and the results of correlations between textile thermal properties and thicknesses; and*
- *the results obtained with thermal sweating cylinder measurements (the heat loss from the cylinder in dry and sweating tests, thermal and corrected thermal resistance, and water vapour transmission).*

The results for the thermal properties, evaluated with the hot-plate apparatus and the Gore & Associates, Inc. method (cf. Table 4), and the results showed in Figures 6a, 7a, 7c and 8b are partly published in Celcar et al [26]. For a better understanding and comparison of thermal properties, evaluated with different measurement systems and under different environmental conditions, the same results are published in this paper as well.

[26], vendar smo jih zaradi lažjega razumevanja in primerjave toplotnih lastnosti, izmerjenih na različnih merilnih napravah in pri različnih klimatskih razmerah, objavili v tem prispevku.

Iz rezultatov meritev toplotnega upora, dobljenega s pomočjo toplotne plošče in merilne naprave Permetest (preglednica 4) ter korelacijske analize med debelino in toplotnim uporom (slika 3) je videti, da se z naraščanjem debeline materiala vrednost toplotnega upora sorazmerno povečuje. Statistična analiza odvisnosti med izmerjeno debelino in toplotnim uporom je pokazala, da obstajajo statistično pomembne korelacije med debelino analiziranih ploskih tekstilij in toplotnim uporom tekstilij, izmerjenim s toplotno ploščo (slika 3 a), ter korelacije med debelino in toplotnim uporom tekstilij, izmerjenim z merilno napravo Thermo Labo II (slika 3 b). Volnena tkanina iz 100-odstotnega kašmirja z oznako TK09, uporabljena za moški plašč, katere debelina je 1,71 mm, izkazuje najvišjo vrednost toplotnega upora, medtem ko ima 100-odstotna viskozna tkanina z oznako TK12, namenjena za izdelavo podloge moške obleke, ki izkazuje najmanjšo vrednost debeline, najnižjo vrednost toplotnega upora. Iz primerjave vrednosti toplotnega upora tkanin za moško obleko je videti, da ima najvišjo vrednost toplotnega upora 100-odstotna volnena tkanina (TK01), preostali dve tkanini, mešanici volnenih in poliamidnih ter volnenih in elastanskih vlaken, pa imata le nekoliko manjši toplotni upor. Za volnena vlakna je značilno, da so slabi prevodniki toplote, kar potrjuje tudi nižja vrednost koeficienta toplotne prevodnosti. Iz rezultatov toplotnega upora tkanin za podlogo moške obleke in pla-

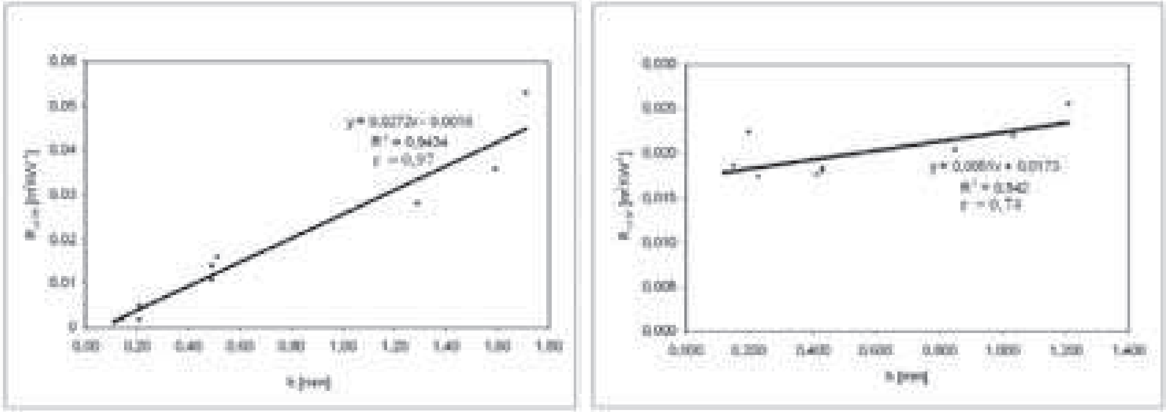
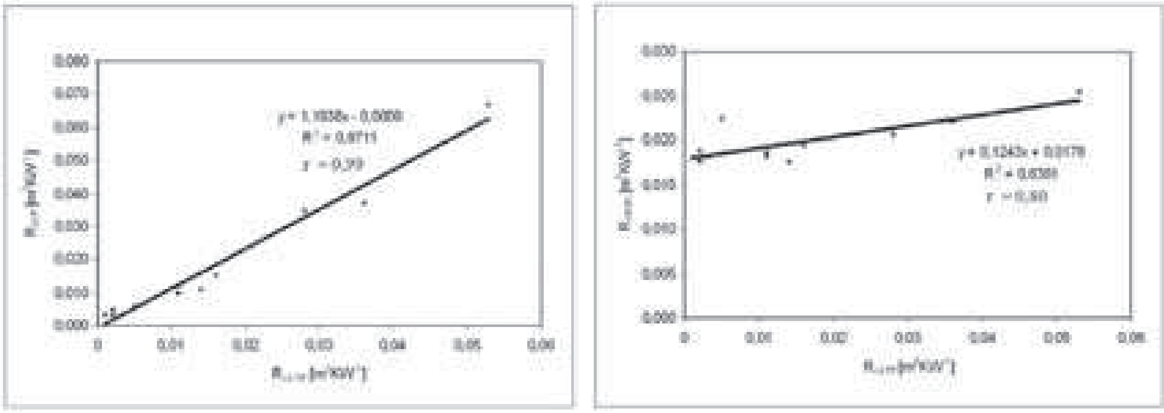
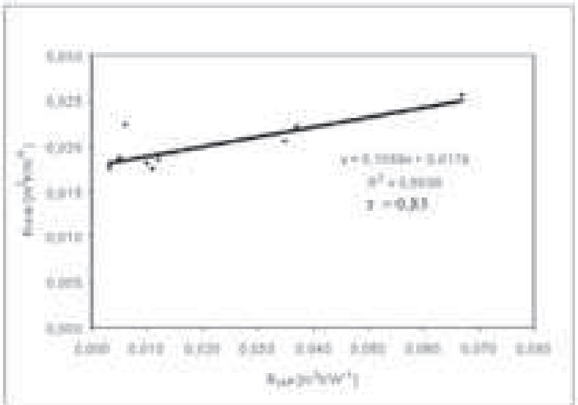


Figure 3: Correlation between thermal resistance evaluated with the hot-plate apparatus $R_{ct\text{-}TP}$ and textile thickness (a), and correlation between thermal resistances evaluated with the Thermo Labo II measurement system $R_{ct\text{-}SK}$ and textile thickness (b)

From the thermal resistance values evaluated with the hot-plate apparatus and the Permetest measurement system (cf. Table 4), and the correlation analysis between thickness and textile thermal resistance (cf. Figure 3), it is ev-

šča je videti, da so vrednosti toplotnega upora zelo nizke. Prav tako je iz rezultatov toplotnega upora tkanin za podlogo moške obleke videti, da se vrednosti le-tega bistveno ne razlikujeta, čeprav je tkanina z oznako TK21 zaradi nanosa PCMs debelejša glede na konvencionalno podlogo tj. tkanino z oznako TK12.





a) Correlation between textile thermal resistance evaluated with the hot-plate apparatus $R_{ct\text{-}TP}$ and Permetest measuring system $R_{ct\text{-}P}$
b) Correlation between textile thermal resistance evaluated with the hot-plate apparatus $R_{ct\text{-}TP}$ and Thermo Labo II measuring system $R_{ct\text{-}SK}$
c) Correlation between textile thermal resistance evaluated with the Permetest $R_{ct\text{-}P}$ and Thermo Labo II measuring system $R_{ct\text{-}SK}$

Figure 4: Correlation between the textile thermal resistances (R_{ct}) evaluated with the hot-plate apparatus ($R_{ct\text{-}TP}$), Permetest measurement system ($R_{ct\text{-}P}$) and Thermo Labo II measurement system ($R_{ct\text{-}SK}$)

ident that by increasing textile thickness, thermal resistance values proportionally increase. A statistical analysis between measured thickness and textile thermal resistance showed that statistically important correlations exist between thickness and textile thermal resistance, evaluated with a hot-plate apparatus (cf. Figure 3a), as well as correlations between thickness and textile thermal resistance evaluated by using the Thermo Labo II measurement system (cf. Figure 3b). It is evident that the 100% cashmere fabric (TK09, used for coats) 1.71 mm in thickness has the highest thermal resistance value, while the 100% viscose fabric (TK12, used for suit linings) has the lowest thickness and the lowest thermal resistance value. The thermal resistance values of textiles used for male suits show that the 100% wool fabric (TK01) has the highest value of thermal resistance, while the other two fabrics, a mixture of wool and polyamide (TK02), and a mixture of wool and elastane fibres (TK03), have slightly lower thermal resistance values. Furthermore, fabrics used for lining suits and coats have very low thermal resistance values. By comparing the thermal resistance values of the two fabrics for male suit linings (TK12 and TK21), it can be seen that the values do not differentiate at all despite the fabric coated with phase-change materials, PCMs (TK21), being thicker if compared to the fabric not coated with PCMs (TK12).

A statistical analysis of the textile thermal resistance evaluated by using the hot-plate appa-

Statistična analiza odvisnosti med rezultati toplotnega upora, določenega s pomočjo toplotne plošče in merilne naprave Permetest, je pokazala, da med parametroma obstajajo statistično pomembne korelacije (slika 4a). Vrednost korelacijskega koeficienta (r) znaša 0,99, kar pomeni, da gre za statistično dokazano korelacijo med parametroma, izmerjenima na različnih merilnih napravah. Toplotni upor analiziranih ploskih tekstilij R_{ct}, dobljen z merilno napravo Thermo Labo II, je določen po dveh metodah, in sicer po suhi kontaktni metodi $R_{ct\text{-}SK}$, kjer je preizkušanec v neposrednem stiku s toplotnim telesom, ter po suhi brezkontaktni metodi $R_{ct\text{-}SBK}$, kjer je med toplotnim telesom in preizkušancem vstavljen še okvir z mrežico, s čimer se simulira zračni sloj. Iz rezultatov toplotnega upora je videti, da ima najvišjo vrednost tkanina za moški plašč, tj. tkanina z oznako TK09, najnižjo vrednost pa ima tkanina za podlogo moške obleke z oznako TK21, preglednica 5. Toplotni upor tekstilij, določen po suhi brezkontaktni metodi, je v povprečju za 55 % višji od toplotnega upora, določenega po suhi kontaktni metodi. Statistična analiza odvisnosti med toplotnim uporom, izmerjenim s pomočjo merilne naprave Thermo Labo II po suhi kontaktni metodi, in toplotnim uporom, izmerjenim s toplotno ploščo in z merilno napravo Permetest, je pokazala, da med parametri obstajajo statistično pomembne korelacije (sliki 4b in 4c). Vrednost korelacijskega koeficienta v prvem primeru (slika 4b) znaša 0,80, medtem ko vrednost korelacijskega koeficienta v drugem primeru (slika 4c) znaša 0,83. Iz tega lahko povzamemo, da med vrednostmi toplotnega upora, izmerjenega z merilno napravo Thermo Labo II, s toplotno ploščo in z merilno napravo Permetest, obstaja linearna povezava.

Prav tako je bilo na podlagi rezultatov toplotnega upora ($R_{\lambda\text{-}TL}$), določenega iz kvocienta debeline in toplotne prevodnosti, dobljene z merilno napravo Thermo Labo II, ter s toplotnim uporom (R_{ct}), dobljenim s toplotno ploščo in z merilno napravo Permetest, ugotovljeno, da obstajajo statistično pomembne korelacije (sli-

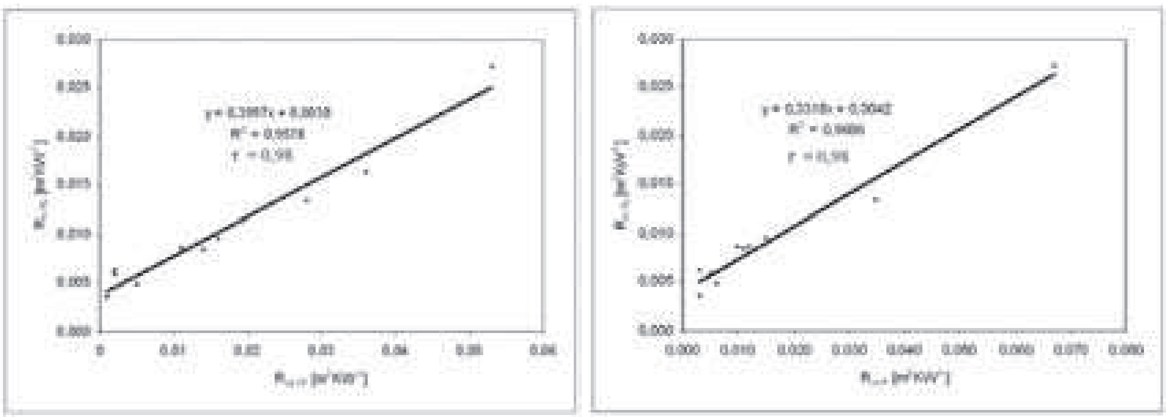


Figure 5: Correlation between textile thermal resistance by conduction evaluated with the Thermo Labo II measurement system $R_{\lambda\text{-}TL}$ and textile thermal resistance evaluated with the hot-plate apparatus $R_{ct\text{-}TP}$ (a) and Permetest measurement system $R_{ct\text{-}P}$ (b)

ratus and the Permetest measurement system showed that statistically significant correlations (the value of correlation coefficient (r) is 0.99) exist between parameters (cf. Figure 4a). The thermal resistance evaluated with the Thermo Labo II measurement system is determined according to two methods, i.e. the dry contact method ($R_{ct\text{-}SK}$), where the sample is in direct contact with the hot plate, and the dry non-contact method ($R_{ct\text{-}SKB}$), where a constant distance space between the sample and the hot plate is maintained. The results show that the fabric TK09, used for coats, has the highest value, and the fabric TK21, used for lining suits, has the lowest value of thermal resistance evaluated with the Thermo Labo II measurement system (cf. Table 5). The thermal resistance values determined according to the dry non-contact method are by approximately 55% higher than the values determined according to the dry contact method. The statistical analysis of the textile thermal resistance evaluated with the dry contact method using the Thermo Labo II measurement system and the thermal resistance evaluated using the hot-plate apparatus, and the Permetest measurement system pointed out statistically significant correlations between the parameters (cf. Figure 4b and 4c). The value of the correlation coefficient (r) in the first case is 0.80 (cf. Figure 4b), while it is 0.83 in the second case (cf. Figure 4c). It can be concluded that linear connections exist between the textile thermal resistance values evaluated with the Thermo Labo II measurement system, the hot-plate apparatus, and the Permetest measurement system.

The results of the textile thermal resistance values by conduction ($R_{\lambda\text{-}TL}$) determined with the quotient of the textile thickness and thermal conductivity evaluated with the Thermo Labo II measurement system, the textile thermal resistance evaluated using the hot-plate apparatus, and the Permetest measurement system, leads to the existence of statistically significant correlations (cf. Figure 5a and b). The latter means that there are linear connections between these parameters. The highest values of warm-cool feeling (q_{max}), determined with the Thermo Labo II measurement system (cf. Table 5), are attained at the fabrics used for lin-

ki 5a in 5b). Vrednost korelacijskega koeficienta v obeh primerih znaša 0,98, kar pomeni, da obstaja linearna povezava med omenjenima parametroma.

Iz rezultatov toplo-hladnega občutka q_{max} (preglednica 5), ki je bil določen s pomočjo merilne naprave Thermo Labo II, je videti, da imajo najvišje vrednosti parametra tkanine za podlogo moške obleke in plašča (najvišjo vrednost ima tkanina z oznako TK12), sledi jim tkanina za moško srajco z oznako TK07, kar pomeni, da omenjene tkanine dajejo hladnejši občutek v primerjavi z drugimi tekstilijami, ki imajo nižje vrednosti toplo-hladnega občutka. Višje vrednosti povedo, da ploska tekstilija daje hladnejši občutek in nasprotno, kar pomeni, da tkanina z oznako TK12, tj. 100-odstotna viskozna tkanina za podlogo moške obleke, daje najhladnejši občutek, tkanina z oznako TK09, tj. 100-odstotna kašmirska dlaka, pa najtoplejši občutek. Sposobnost zadrževanja toplote, ki je izražena s koeficientom ohranjanja toplote (α), je izračunana iz vrednosti izgub toplotnega toka, izmerjenega s pomočjo merilne naprave Thermo Labo II po dveh metodah, in sicer na podlagi suhe kontaktne metode (α_{SK}) in suhe brezkontaktne metode (α_{SBK}). Vrednosti koeficienta ohranjanja toplote, dobljene po suhi brezkontaktni metodi, so za 30 do 60 % višje od vrednosti koeficienta, dobljenega po suhi kontaktni metodi. To pomeni, da pri suhi brezkontaktni metodi, kjer je med toplotnim telesom in preizkušancem zračni sloj, ki je toplotni izolator, le-ta povečuje sposobnost zadrževanja toplote. Iz rezultatov je videti, da najnižjo vrednost koeficienta ohranjanja toplote pri suhi kontaktni metodi izkazujeta tkanini s fazno spremenljivimi materiali v/na površini tekstilije, to sta tkanini z oznako TK21 in TK22, najvišjo vrednost sposobnosti zadrževanja toplote pa kaže tkanina za moški plašč, z oznako TK09, sledi ji tkanina za srajco, z oznako TK07, tej pa pletivo za spodnje perilo z oznako TK15. Iz rezultatov meritev upora ploskih tekstilij proti prehodu vodne pare (R_{et}), ki je bil določen s pomočjo merilne naprave Permetest (preglednica 4) je videti, da je vrednost upora proti prehodu vodne pare najvišja pri bombažnem pletivu z oznako TK15, najnižja pa je bila izmerjena pri viskozni tkanini za podlogo moške obleke z oznako TK12. Meritve kažejo tudi, da ima tkanina z oznako TK21 (100-odstotna viskozna podloga z nanosom PCMs) enkrat višjo vrednost R_{et} kot tkanina z oznako TK12 (100-odstotna viskozna podloga). Zaznana razlika je posledica različnih ploskovnih mas in debelin analiziranih tkanin ter gostote niti in nanosa PCMs, ki zmanjšuje prenos vodne pare skozi plosko tekstilijo in povečuje upor proti prehodu vodne pare. Statistična primerjava debeline uporabljenih ploskih tekstilij z uporom tekstilije proti prehodu vodne pare je pokazala, da med parametroma obstajajo statistično pomembne korelacije s koleracijskim koeficientom (r) 0,96. To pomeni, da z naraščanjem debeline materiala vrednost upora proti prehodu vodne pare sorazmerno narašča.

Rezultati analize vpliva klimatskih razmer in stopnje znojenja na vrednosti suhega (ϕ_c) in evaporativnega (ϕ_e) toplotnega toka kom-

ing suits and coats, and male shirts (TK07), which means that these fabrics offer a cooler feeling compared to other fabrics with lower values of warm-cool feeling. If a fabric has a high warm-cool value, it gives a cooler feeling and, inversely, a fabric with a lower warm-cool value gives a warmer feeling. This means that the fabric TK12, a 100% viscose fabric for lining suits, offers the coolest feeling of all, and the fabric TK09, a 100% cashmere fabric for coats, the warmest feeling. The heat-keeping property (α) was determined from the heat-flow values measured by using the Thermo Labo II measurement system compared to the other two methods, i.e. the dry contact method (α_{SK}) and the dry non-contact method (α_{SBK}). The heat-keeping values determined according to the dry non-contact method are higher by 30–60% than the heat-keeping values determined according to the dry contact method. This means that for the dry non-contact method, with a constant distance air space between the sample and hot plate, the air-layer functioning as a thermal isolator increases the ability to keep heat. The results in Table 5 show that the lowest value of the heat-keeping property determined by

binacij ploskih tekstilij so prikazani na slikah 6 in 7. Analiza suhega toplotnega toka, ki ga je cilinder oddal pri različnih temperaturah zraka (slika 6), je pokazala, da z naraščajočo temperaturo zraka padajo vrednosti suhega toplotnega toka in nasprotno, s pojemajočo temperaturo zraka naraščajo. To pomeni, da je prenos suhega toplotnega toka odvisen od razlike med temperaturo na površini cilindra in temperaturo zraka v okolici, torej od temperaturnega gradienta ter toplotnega upora kombinacije tekstilij. Pri tem lahko poudarimo, da je cilinder v toplo-hladnem okolju pri temperaturi zraka 10 °C oddal za približno 60,6 % več toplote kot pri 25 °C, da je obdržal konstantno temperaturo na površini cilindra. Tudi iz rezultatov v hladno-mrzlem okolju je videti, da cilinder pri temperaturi zraka –5 °C v povprečju odda za 32,2 % več toplote kot pri 10 °C, da obdrži konstantno temperaturo kože oziroma temperaturo na površini cilindra, saj je temperaturna razlika med površino cilindra in temperaturo zraka dokaj velika in znaša 40 °C. Dalje je iz primerjave suhega toplotnega toka, izmerjenega v toplo-hladnem in hladno-mrzlem okolju pri temperaturi zraka 10 °C, videti, da so vrednosti suhega toplotnega toka v prvem primeru v povprečju za 25,5 % višje od vrednosti v drugem primeru, kjer je v kombinacijo oblačilnega sistema vključen še sloj ploske tekstilije za moški plašč, tj. tkanina z oznako TK09, in podloga za plašč, tj. tkanina z oznako TK14. To pomeni, da so kombinacije ploskih tekstilij z dodatnim slojem za plašč in podlogo zmanjšale prehod toplote skozi sloje tekstilij, kar zagotavlja boljšo toplotno zaščito.

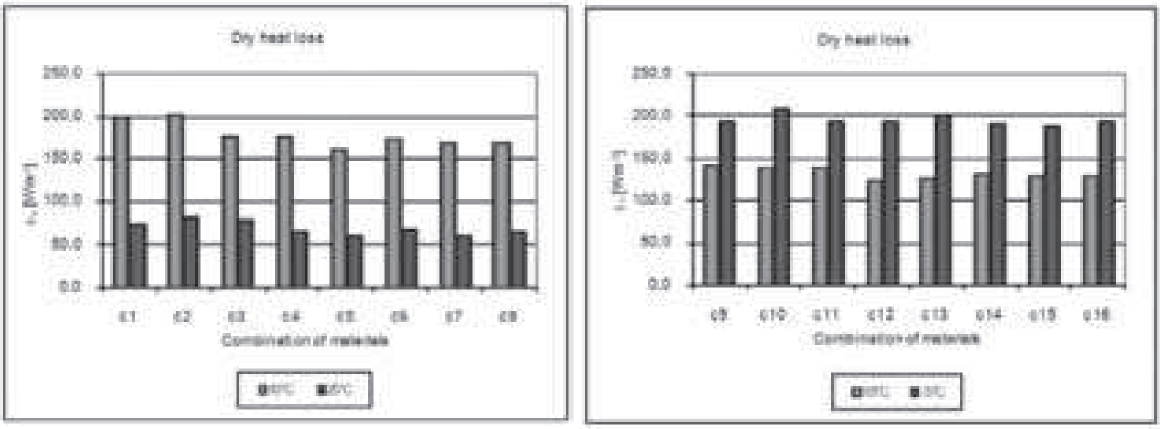


Figure 6: Dry heat loss ϕ_c from the cylinder through combinations of clothing materials at different ambient temperatures

using the dry contact method characterises the fabrics with phase-change materials (TK21 and TK22), the highest value has the fabric used for coats (TK09), followed by the fabrics for shirts (TK07) and knitwear for underwear (TK15). The results for textile water vapour resistances (R_{et}) evaluated with the Permetest meas-

Analiza suhega toplotnega toka in toplotnega upora izbranih kombinacij ploskih tekstilij je pokazala, da vrednosti suhega toplotnega toka in toplotnega upora analiziranih kombinacij ploskih tekstilij kažejo le manjša odstopanja. Ugotovljeno je, da kombinacija ploskih tekstilij z oznako c2 v toplo-hladnem okolju in kombinacija z oznako c10 v hladno-mrzlem okolju pri večini klimatskih razmer izkazujeta najvišje vrednosti suhega toplotnega toka. Prav *urement system (cf. Table 4) reveal that cotton knitwear (TK15) has the highest value of water vapour resistance, while the 100% viscose fabric for lining suits (TK12) has the lowest. It is also evident from the results that the fabric TK21 (100% viscose liner coated with PCMs) has a double value of R_{et} if compared to the fabric TK12 (100% viscose liner without PCMs). The difference is a consequence of different weights, textile thicknesses, yarn densities and PCM coatings that reduce water vapour transmission through fabrics and increase the textile water vapour resistance. The statistical analysis when comparing the textile thicknesses using water vapour resistance pointed out the existence of statistically significant correlations (r = 0.96), which means that by increasing textile thicknesses, the values of textile water vapour also proportionally increase.*

The results for the measured heat loss values from the cylinder for the dry (ϕ_c) and sweat

tako je iz rezultatov primerjave suhega toplotnega toka analiziranih kombinacij ploskih tekstilij z oznakami od c1 do c4 in od c5 do c8, ki se razlikujejo le v sloju ploske tekstilije za podlogo moške obleke (v kombinaciji od c5 do c8 je uporabljena podloga s PCMs-nanosom), videti, da kombinacije od c5 do c8 izkazujejo nižje vrednosti suhega toplotnega toka in višje vrednosti toplotnega upora. Pri tem je zanimivo, da se vrednosti suhega toplotnega toka pri kombinacijah z oznakama c4 in c8 bistveno ne razlikujejo (v obeh primerih je kot osnovna tkanina za moško obleko uporabljena tkanina z oznako TK22, tj. tkanina z vsebnostjo PCMs). Pri drugih kombinacijah pa so opazne večje razlike, ki so statistično pomembne. Tudi iz rezultatov suhega toplotnega toka pri kombinacijah ploskih tekstilij z oznakami od c9 do c12 in od c13 do c16 je videti, da kombinacije z oznakama c9 in c12 izkazujejo nižje vrednosti suhega toplotnega toka in višje vrednosti toplotnega upora. Vrednosti suhega toplotnega toka kombinacije z oznakama c12 in c16 se bistveno ne razlikujeta od drugih kombinacij. Kljub omenjenim razlikam v suhem toplotnem toku in toplotnem uporu analiziranih kombinacij ploskih tekstilij je videti, da imajo kombinacije, v katerih je podloga z oznako TK21, tj. 100-odstotna viskozna podloga z nanosom PCMs- materialov, višje vrednosti to-

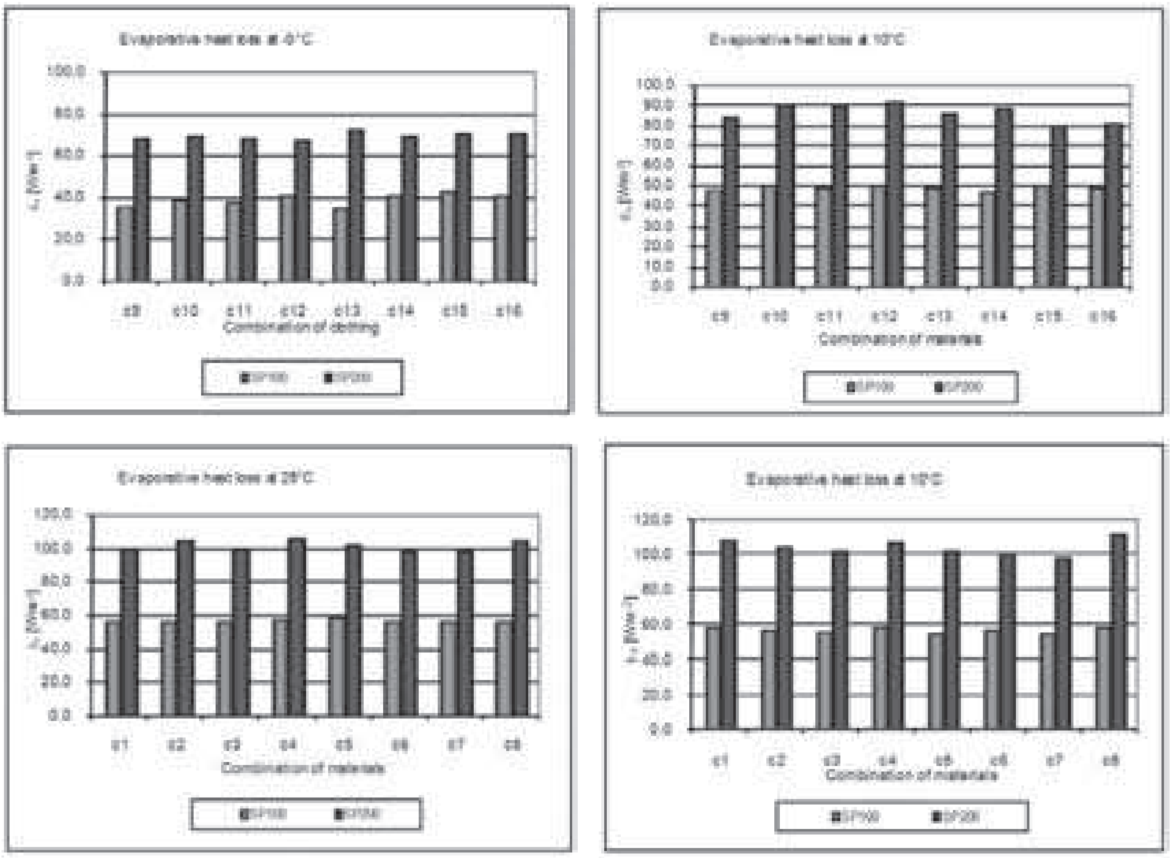


Figure 7: Evaporative heat loss (ϕ_e) from the cylinder through combinations of clothing materials at 10 °C (a [26] and b), 25 °C (c [26]) and −5 °C (d) ambient temperatures and two sweating levels (SP100 and SP200)

tests (ϕ_e) through combinations of clothing materials under different environmental conditions are shown in Figures 6 and 7.

The analysis of the dry heat losses from the cylinder under different environmental conditions (cf. Figure 6) showed that by increasing the ambient temperature, the values of dry heat loss decrease and, inversely, by declining the ambient temperature, they increase. This means that dry heat transfer depends on the difference between the cylinder surface temperature and ambient temperature, and the thermal resistances of material combinations. It is evident that a cylinder in the warm-cool environment at the ambient temperature 10 °C gives away by approx. 60.6% more heat than at 25 °C, hence maintaining a constant surface temperature. From the results gained in a cool-cold environment, it can be noted that the cylinder at the average ambient temperature −5 °C gives away by approx. 32.2% more heat than at 10 °C. The results gained at the ambient temperature 10 °C in warm-cool and cool-cold environments show that the values of dry heat losses in warm-cool environments are on average by 25.5% higher than the values in cool-cold environments, where the material combinations include two extra layers, i.e. the fabric for coats (TK09) and the liner-fabric for coats (TK14). This leads to the conclusion that these extra layers reduce the heat transfer through the combination of materials and cause better thermal protection against cold. From the analysis of the dry heat loss values and thermal resistance values of different combinations of materials, it is evident that the combination c2 in a warm-cool environment and the combination c10 in a cool-cold environment have the highest values of dry heat loss at most environmental conditions. By comparing the combinations c1−c4 with c5−c8, which are different (viscose liner coated with PCMs is used in the combination c5−c8), and thicker liner-layers, it can be seen that the heat loss values in the combinations c5−c8 are slightly lower due to the thicker liner-layers and that the values of thermal resistance are higher. The dry heat loss values measured for the combination c4 and c8 do not differ essentially; in both combinations, the fabric used for suits (TK22) with incorporated PCMs was used. In contrast,

plotnega upora kot kombinacije s konvencionalno 100-odstotno viskozno podlogo.

Meritve evaporativnega toplotnega toka (φ_e), slika 7, ki je potreben za evaporacijo vode, ter skupnega toplotnega toka pri znojenju (φ_{sw}), ki sta bila določena pri dveh stopnjah znojenja (SP100 in SP200), kažejo, da z naraščajočo stopnjo znojenja narašča vrednost evaporativnega toplotnega toka in s tem tudi toplotnega toka pri znojenju, kar pomeni, da je za evaporacijo večje količine vode potreben večji evaporativni toplotni tok. Pri tem je bilo ugotovljeno, da so vrednosti evaporativnega toplotnega toka pri stopnji znojenja SP200 pri temperaturi zraka 25 °C v povprečju za 43,9 % večje od vrednosti, dobljenimi pri SP100, medtem ko so pri temperaturi zraka 10 °C vrednosti evaporativnega toplotnega toka v toplo-hladnem okolju pri stopnji znojenja SP200 v povprečju za 46,3 %, v hladno-mrzlem okolju pa za 43,1 % večje od vrednosti, dobljene pri stopnji znojenja SP100. Primerjava evaporativnega toplotnega toka pri temperaturi zraka −5 °C in dveh stopnjah znojenja kaže, da so vrednosti evaporativnega toplotnega toka pri stopnji znojenja SP200 v povprečju za 43,9 % večje od vrednosti pri stopnji znojenja SP100. Analiza toplotnega toka, ki ga cilinder odda pri znojenju in evaporativnega toplotnega toka (slika 7) pri analiziranih kombinacijah tekstilij pri različnih temperaturah zraka in dveh stopnjah znojenja je pokazala, da se omenjena parametra s temperaturo zraka in stopnjo znojenja spreminjata, saj se temperaturni gradient spreminja.

Na sliki 8 so prikazani rezultati vrednosti toplotnega upora ($R_{ct,tot}$) in korigiranega toplotnega upora ($R_{ct,corr}$), ki pomeni upor kombinacije ploskih tekstilij pri znojenju, in rezultati vrednosti sposobnosti prehoda vodne pare skozi kombinacijo ploskih tekstilij (M_e) pri temperaturi zraka 25 °C. Vrednost sposobnosti prehoda vodne pare skozi kombinacijo ploskih tekstilij je izražena kot odnos med količino evaporirane vodne pare (m_e) in količino vode, dovedene v cilinder (m_i). Iz primerjave rezultatov korigiranega toplotnega upora pri dveh stopnja znojenja SP100 in SP200 ter toplotnega upora, ki pomeni upor proti suhemu prehodu toplote (slika 8a), je videti, da se s stopnjo znojenja vrednost toplotnega upora zmanjša, kar pomeni, da oblačilo daje manjšo toplotno zaščito. Tako je iz rezultatov pri temperaturi zraka 25 °C videti, da so pri stopnji znojenja SP100 vrednosti korigiranega toplotnega upora v povprečju za 14,4 %, pri SP200 pa kar za 23,9 % nižje glede na vrednosti toplotnega upora. Analiza korigiranega toplotnega upora $R_{ct,corr}$ (slika 8a), ki pomeni toplotni upor kombinacije ploskih tekstilij pri znojenju, kjer je toplotni tok delno uporaben za evaporacijo vode, je pokazala, da se z naraščajočo stopnjo znojenja vrednosti korigiranega toplotnega upora zmanjšujejo. Pri tem lahko omenimo, da so vrednosti korigiranega toplotnega upora pri temperaturi zraka 25 °C in stopnji znojenja SP200 v povprečju za 11,2 % nižje od vrednosti upora pri stopnji znojenja SP100. Analiza rezultatov sposobnosti prehoda vodne pare skozi kombinacije ploskih tekstilij (slika 8b) je pokazala, da z naraščajočo stopnjo znojenja,

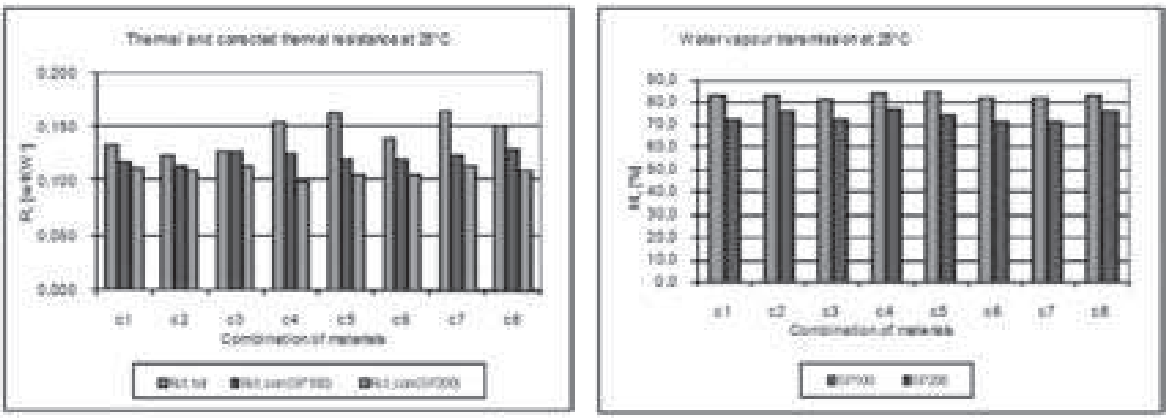


Figure 8: Thermal resistance ($R_{ct,tot}$), corrected thermal resistance ($R_{ct,corr}$) (a) and water vapour transmission (M_e) (b [26]) for combinations of clothing materials at ambient temperature 25 °C

at other combinations, statistically significant greater differences were noted. By comparing the combinations c9–c12 with c13–c16, it can be seen that the combinations c9–c12 have lower dry heat loss values and higher thermal resistance values. The measured values of dry heat losses of the combination c12 and c16 do not differ essentially if compared to other combinations. In spite of the noted differences in dry heat loss and the thermal resistance values of material combinations, it is evident that the combinations with 100% viscose liner coated with PCMs (TK21) have higher values of thermal resistance compared to the combinations with 100% viscose liners without PCMs.

By comparing the evaporative heat loss values (ϕ_e) (cf. Figure 7), which are required for water evaporation, and the total heat loss values during the sweating process (ϕ_{sw}) determined at two sweating levels (SP100 and SP200), it can be noted that by increasing the sweating level, the evaporative heat loss values and total heat loss values during the sweating process increase as well. This means that for a higher amount of evaporating water, a higher amount of evaporative heat loss is needed. The values of the evaporative heat losses at the sweating level SP200 and ambient temperature 25 °C are on average by 43.9% higher in comparison to the values gained at the sweating level SP100. At the ambient temperature 10 °C, the values of the evaporative heat losses at the sweating level SP200 in a warm-cool environment are by 46.3% higher than at SP100, and in a cool-cold environment

sposobnost prehoda vodne pare pada, kar pomeni, da ob povečanem znojenju sloji kombinacij ploskih tekstilij manj prepuščajo evaporirano vodno paro. Pri tem je bilo ugotovljeno, da je sposobnost prehoda vodne pare pri temperaturi zraka 25 °C in stopnji znojenja SP100 v povprečju za 10,7 % višja kot pri stopnji znojenja SP200.

5 Sklep

Raziskava vrednotenja toplotnih lastnosti ploskih tekstilij na različnih merilnih napravah je pokazala, da obstaja korelacija med toplotnim uporom ploskih tekstilij, izmerjenim s toplotno ploščo, merilnima napravama Permetest in Thermo Labo II. Prav tako je bilo potrjeno, da se z naraščajočo debelino materiala vrednost toplotnega upora in upora proti prehodu vodne pare ploskih tekstilij sorazmerno povečuje. Pokazalo se je, da 100-odstotna kašmirska volnena tkanina z največjo debelino izkazuje najvišjo vrednost toplotnega upora, medtem ko ima 100-odstotna viskozna tkanina z najmanjšo debelino najnižjo vrednost toplotnega upora in upora proti prehodu vodne pare; najvišjo vrednost upora proti prehodu vodne pare pa ima bombažno pletivo. Hkrati je bilo ugotovljeno, da obstaja korelacija med toplotnim uporom, določenim iz kvocienta debeline in toplotne prevodnosti, dobljene z merilno napravo Thermo Labo II, ter toplotnim uporom, dobljenim s toplotno ploščo in z merilno napravo Permetest. Vrednosti koeficienta ohranjanja toplote kažejo, da pri suhi brezkontaktni metodi, kjer je med toplotnim telesom in preizkušancem zračni sloj, ki je toplotni izolator, le-ta povečuje sposobnost zadrževanja toplote.

Na podlagi analize rezultatov toplotnih lastnosti analiziranih kombinacij ploskih tekstilij, določenih s pomočjo toplotnega cilindra s simulacijo znojenja, je bilo ugotovljeno, da so analizirane toplotne lastnosti, tj. suhi in evaporativni toplotni tok ter sposobnost prehoda vodne pare, odvisne od klimatskih razmer oziroma tempe-

by 43.1%. By comparing the evaporative heat loss values measured at the ambient temperature −5 °C, it can be noted that the values at the sweating level SP200 are by 43.9% higher than those at the sweating level SP100. The analysis of heat losses during the sweating process (cf. Figure 7) showed that the evaporative heat loss and the total heat loss during the sweating process change with the ambient temperature and sweating level.

Figure 8 shows the values of thermal ($R_{ct,tot}$) and corrected thermal resistance ($R_{ct,corr}$), as well as the values of water vapour transmission (M_e) of the tested material combinations at the ambient temperature 25 °C.

By comparing the corrected thermal resistance values, which represent the resistances of material combinations during the sweating process, measured at two sweating levels, SP100 and SP200 (cf. Figure 8a), it can be seen that by increasing the sweating level, the corrected thermal resistance of the material combination reduces. It is noted that the corrected thermal resistance values measured at the ambient temperature 25 °C and the sweating level SP200 are on average by 11.2% lower than at SP100. The measured results at the ambient temperature 25 °C demonstrate that the corrected thermal resistance values at the sweating level SP100 are on average by 14.4% and at SP200 by 23.9% lower than the thermal resistance values (cf. Figure 8a). This means that the combinations during the sweating process offer lower thermal protection. The analysis of water vapour transmission values (cf. Figure 8b), which are determined by the amount of evaporated water (m_e) as the percentage of water input (m_s), show that by an increasing the sweating level, the water vapour transmission reduces. Therefore, at higher sweating levels, the combinations of materials transmit less evaporated water. Furthermore, the results measured at the ambient temperature 25 °C show that the water vapour transmission values at the sweating level SP100 are on average by 10.7% higher than at the sweating level SP200.

5 Conclusion

From the results of the evaluated textile thermal properties on different measurement systems, it

raturnega gradienta med površino cilindra in temperaturo zraka, s katerim je povezana količina toplotnega toka, potrebnega za ohranjanje konstantne temperature na površini cilindra. Pokazalo se je, da vrednosti suhega toplotnega toka naraščajo z upadanjem temperature zraka in da vrednosti toplotnega toka pri znojenju z naraščajočo stopnjo znojenja in/ali pojemajočo temperaturo zraka naraščajo. Prav tako je bilo ugotovljeno, da se z različno stopnjo dovedene količine vode v cilinder, torej z različno stopnjo znojenja, vrednosti toplotnih lastnosti spremenijo. Vrednosti toplotnega upora pri znojenju ali t. i. korigiranega toplotnega upora so v primerjavi s toplotnim uporom manjše. Prav tako je bilo ugotovljeno, da z naraščajočo stopnjo znojenja vrednosti evaporativnega toplotnega toka naraščajo, medtem ko vrednosti korigiranega toplotnega upora in vrednosti sposobnosti prehoda vodne pare padajo. To pomeni, da prisotnost procesa znojenja zniža vrednost toplotne zaščite kombinacij ploskih tekstilij. Hkrati je bilo ugotovljeno, da obstajajo majhne razlike v vrednostih suhega toplotnega toka in toplotnega upora med kombinacijami, v katerih je 100-odstotna viskozna podloga (c1-c4, c9-c12) in kombinacijami, ki vsebujejo 100-odstotno viskozno podlogo z nanosom fazno spremenljivih materialov (c5-c8, c13-c16). Ugotovljeno je bilo, da imajo kombinacije z viskozno podlogo z nanosom PCMs višje vrednosti toplotnega upora kot kombinacije z viskozno podlogo brez PCMs.

6 Reference

1. MECHEELS, J. *Körper-Klima-Kleidung. Wie funktioniert unsere Kleidung?* Shiele & Schön. Berlin, 1998.
2. PARSONS, K. C. *Human Thermal Environments. The effects of hot, moderate, and cold environments on human health, comfort and performance*. 2nd Edition published 2003 by Taylor & Francis, London.
3. *ISO 11092: 1993. Textiles-Physiological effects-Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hot plate test). International Organization for Standardization (ISO).* Genève, Switzerland.
4. FRYDRYCH, I., DZIWORSKA, G., BILSKA, J. Comparative analysis of the thermal insulation properties of fabrics made of natural and man-made cellulose fibres. *Fibres & Textiles in Eastern Europe*, 2002, October/December, pp. 40–44.
5. Gibson, P.W. Factors influencing steady-state heat and water-vapor transfer measurements for clothing materials. *Textile Research Journal*, 1993, vol. 63, no 12, pp. 749–764.
6. GUNESOGLU, S., MERIC, B., GUNESOGLU, C. Thermal contact properties of 2-yarn fleece knitted fabrics. *Fibres & Textiles in Eastern Europe*, 2005, April/June, vol. 13, no. 2 (50), pp. 46–50.
7. GOHLKE, D. J. I*mproved analysis of comfort performance in coated fabrics*. W. L. Gore & Associates, Inc., March 1980.

can be noted that statistically significant correlations exist between the parameters of the textile thermal resistances determined with the hot-plate apparatus, Permetest and Thermo Labo II measurement systems. Moreover, the results point out that by increasing the textile thickness, the values of the textile thermal resistance and water vapour resistance increase proportionally. It is noted that a 100% cashmere fabric with the highest thickness has the highest value of thermal resistance, while a 100% viscose fabric with the lowest thickness has the lowest values of thermal resistance and water vapour resistance. Cotton knitwear has the highest value of water vapour resistance. Furthermore, statistically significant correlations exist between the textile thermal resistance by conduction evaluated by using the Thermo Labo II measurement system and the textile thermal resistance evaluated with the hot-plate apparatus, and the Permetest measurement system. From the heat-keeping property evaluated according to the dry non-contact method using the Thermo Labo II measurement system, where a constant distance air space exists between the sample and hot plate, the air layer functioning as a thermal isolator increases the ability to keep heat.

From the thermal property analysis of material combinations evaluated by using a thermal sweating cylinder, it can be seen that the thermal properties, i.e. dry and evaporative heat loss and water vapour transmission, depend on climatic conditions or temperature gradient between the cylinder surface, respectively, and the ambient temperature. The results show that dry heat loss values increase with a decreasing ambient temperature and that the heat loss values in the sweat test increase with an increasing sweating level and/or lower ambient temperatures. It can be noted that different sweating levels influence the thermal properties of material combinations. The measured results of thermal and corrected thermal-resistance values show that the sweating process reduces the thermal protection for material combinations. The thermal property analysis of material combinations, evaluated at different sweating levels, shows that by increasing the sweating level, the evaporative heat loss values increase, while the corrected thermal resistance and water vapour

8. HES, L., DOLEZAL, I. New method and equipment for measuring thermal properties of textiles. *J. Text. Mach. Soc. Jpn.*, 1989, vol. 42, no. 8, pp. 124–128.
9. HES, L., DEARAUJO, M., DJULAY, V.V. Effect of mutual bonding of textile layers on thermal insulation and thermal contact properties of fabric assemblies. *Textile Research Journal*, 1996, vol. 66, no. 4, pp. 245–250.
10. HES, L. Optimisation of shirt fabrics' composition from the point of view of their appearance and thermal comfort. *International Journal of Clothing Science and Technology*, 1999, vol. 11, no. 2/3, pp. 105-119.
11. LE, C. V., LY, N. G., POSTLE, R. Heat and moisture transfer in textile assemblies part I: Steaming of wool, cotton, nylon and polyester fabric beds. *Textile Research Journal*, 1995, vol. 65, no. 4, pp. 203–212.
12. MEINANDER, H. *Introduction of a new test method for measuring heat and moisture transmission trough clothing materials and its application on winter work wear*. VTT Publication 24, Espoo, Finland, 1985.
13. MEINANDER, H. Clothing physiological measurements on winter workwear materials with a sweating cylinder. *Journal of the textile institute*, 1988, Vol 79 No 4, pp. 620-633.
14. MEINANDER, H., RICHARDS, M. and Thermoprotect network. Effects of moisture on the heat transfer through clothing materials. V: *Proceedings of the 11th International Conference on Environmental Ergonomics*, Ystad, 22-26.5.2005. Edited by: Holmer, I., Kuklane, K. and Gao, C. Ystad, Sweden, 2005, pp. 442–444.
15. PAC, M. J., BUENO, M. A., RENNER, M., KASMI, SL. Warm-cool feeling relative to tribological properties of fabrics. *Textile Research Journal*, 2001, vol. 71, no. 9, pp. 806–812.
16. ROSSI, R. M., GROSS, R., MAY, H. Water vapor transfer and condensation effects in multilayer textile combinations. *Textile Research Journal*, 2004, vol. 74, no. 1, pp. 1–6.
17. SCHNEIDER, A. M, HOSCHKE, B. N, GOLDSMID, H. J. Heat transfer through moist fabrics. *Textile Research Journal*, 1992, vol. 62, no. 2, pp. 61–66.
18. UMBACH, K. H. Contribution of the surface characteristics of textiles made from wool to thermophysiological comfort. V: *Proceedings of The 7th International Wool Textile Research Conference*. Tokyo 1985, vol. III, pp. 178–190.
19. HUANG J. Sweating guarded hot plate test method. *Polymer Testing*, 2006, vol. 25, pp. 709–716.
20. HES, L. Permetest instrument. *Sensora Instruments & Consulting*, Liberec, Czech Republic, 2005.
21. *Operating Instruction KES-F7: Manual for KES-F7 Thermo Labo II (Precise and Prompt Thermal Prosperity Measurement Instrument),* The second Edition, Kato Tech Co. Ltd., Japan, 1998.
22. *ISO 5085-1:1989. Textiles-Determination of thermal resistance-Part 1: Low thermal resistance. ISO. Genève, Switzerland.*

transmission values reduce. In consequence, the material combinations offer lower thermal protection during the sweating process. In addition, when dry-testing, small differences in heat loss and thermal resistance values exist between the combinations with 100% viscose liners (c1–c4, c9–c12) and combinations with 100% viscose liners coated with PCMs particles (c5–c8, c13–c16). It is evident that the combinations with a 100% viscose liner coated with PCMs have higher values of thermal resistance if compared to the combinations with a 100% viscose liner without PCMs.

Acknowledgements

We would like to thank Dr Harriet Meinander, who performed this research in the SmartWearLab at the Tampere University of Technology in Finland.

23. *ISO 5084:1996. Textiles-Determination of thickness of textiles and textile products. ISO. Genève, Switzerland.*
24. *ISO 3801:1977. Textiles-Determination of mass per unit length and mass per unit area. ISO. Genève, Switzerland.*
25. *ISO 9237:1995. Textiles-Determination of the permeability of fabrics to air. ISO. Genève, Switzerland.*
26. CELCAR, D., MEINANDER, H., GERŠAK, J. A study of the influence of different clothing materials on heat and moisture transmission through clothing materials, evaluated using a sweating cylinder. *International Journal of Clothing Science and Technology,* 2008, vol. 20, no. 2, pp. 119–130.

Zahvala

Zahvaljujemo se dr. Harriet Meinander, ki je omogočila izvedbo raziskovalnega dela v laboratoriju SmartWearLab na Tampere University of Technology na Finskem.