

# A SUBJECTIVE EVALUATION OF THE THERMAL COMFORT OF CLOTHING EVALUATED IN COLD ENVIRONMENT

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ISSN 2232-755X

DOI: 10.7251/GHTE1410065C

UDC: 677.017.82

Original scientific paper

*In this study, the thermal comfort of clothing was subjectively evaluated in cold environmental conditions. Different male business clothing systems, made of standard textiles (wool and wool-mixture), and materials that contain phase-change materials (PCMs), were developed. The research was performed with the help of test subjects in a computer controlled climatic chamber, in artificially created cold environmental conditions, at ambient temperatures of 10 °C, 5 °C and 0 °C, and with physical activity that is as reminiscent as possible of the real life situation of wearing clothes, such as sitting and walking on a treadmill. The impact of particular business clothing systems and varied cold environmental conditions on the wearer's subjective feeling of thermal comfort was determined with a questionnaire and an assessment scale of thermal comfort defined by standard ISO 10551:2004. For this purpose, an analysis of the subjective evaluation of thermal comfort, the desired thermal state, the acceptability of the current situation and their personal tolerance of the environment, was made before, during and after each experiment. The results of the research show that subjective evaluations of thermal comfort directly depend on environmental conditions, as well as clothing systems. From this subjective evaluation it can be seen that in spite of lower mean skin temperatures the test subjects felt comfortable at an ambient temperature of 10 °C. It is also evident that the analysed clothing systems are not suitable for wearing below an ambient temperature of 0 °C, because the test subjects felt uncomfortable.*

**Key words:** thermal comfort, subjective evaluation, phase-change materials (PCMs), clothing, cold environment

## INTRODUCTION

Clothing wear comfort is a state of mind influenced by a range of factors, such as the temperature of the environment, the relative humidity, the wind velocity, the metabolism of the wearer, the characteristics the clothing materials e.g. materials' thermal comfort properties, and is the result of a balanced process of heat exchange between the human body, the clothing system and the environment.

Many other factors such as colour, fashion, a person's physical and psychological state also influence the feeling of comfort (1). The feeling of comfort is one of the key factors when selecting clothing, and a decisive factor in the evaluation of the clothing quality. It is also an important factor in business garments, since they are intended to be worn throughout the whole day in different environmental conditions.

Garments are a heat exchange layer between the body and its environment. Because of this, and because contemporary requirements regarding clothing comfort are much higher than in the past, we have decided to investigate the impact of different cold environmental conditions on the subjective feeling of the thermal comfort provided by different male business garments, as well as the male business clothing that contains phase-change materials (PCMs) used as both the lining and outerwear material. Phase-change materials, also called latent heat storage materials, are materials that can absorb, store and release thermal energy as latent heat, while they go through a solid-liquid transition. They were developed to regulate the human body temperature fluctuations, assuring the thermal physiological comfort of the wearer (2, 3). Currently, PCMs are being used in a variety of outdoor apparel items (e.g. underwear, socks, gloves, jackets, sportswear, shoes, protective wear) (4), therefore, we decided to incorporate those materials into male business clothing with the purpose of finding out if these materials in combination with common textile materials for business clothing are able to interact with the human body and produce thermoregulatory control by affecting the microclimate between the clothing and the human skin under different environmental conditions.

The impact of particular business clothing systems, with and without PCMs, on the subjective assessment of the thermal comfort of clothing in cold environmental conditions at ambient temperatures of 10 °C, 5 °C and 0 °C was determined experimentally with the help of test subjects according to standard ISO 10551:2004 (5). For this purpose a questionnaire and an assessment scale were used before, during and after each experiment, in order to evaluate the wearer's subjective feeling of thermal comfort.

## MATERIALS AND METHODS

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*Experimental clothing ensembles*

Five male business clothing ensembles of 4-layer clothing system (short underwear, long sleeve male shirt, male suit with lining and long male coat with lining) were developed for this study (Table 1). The same underwear, male shirt and male coat with lining were used for testing. In this research we varied textile materials of male suits and linings for the male suit. The thermal comfort properties of male business clothing systems were measured by using a sweating thermal manikin Coppelius under different environmental and sweating conditions and are published in Celcar et al.'s work (6).

*Subjects*

Five male persons between 21 and 23 years of age ( $22.2 \pm 0.8$ ) participated in the wear trial test. They were on average 180.2 cm tall ( $180.2 \pm 4.6$ ) and of the average weight of 80.0 kg ( $80.0 \pm 2.4$ ). The general purpose, procedure and risks were fully explained, and informed consent was given by all subjects, but they were not informed about the details of the clothing materials, in order to avoid any influence on their subjective ratings.

Table 1: Clothing ensembles of business clothing systems with fibre content of textile materials

Combination of clothing system	Fibre content of textile materials					
	Underwear	Shirt	Male suit	Lining for jacket	Male coat	Lining for coat
cs6	100 % CO	78 % CO, 22 % PES	100 % WO	100 % CV	100 % WS	100 % CV
cs7	100 % CO	78 % CO, 22 % PES	88 % WO in 12 % PA	100 % CV	100 % WS	100 % CV
cs8	100 % CO	78 % CO, 22 % PES	98 % WO in 2 % EL	100 % CV	100 % WS	100 % CV
cs9	100 % CO	78 % CO, 22 % PES	68 % Outlast: Acryl with PCMs, 28 % WO, 4 % EL	100 % CV	100 % WS	100 % CV
cs10	100 % CO	78 % CO, 22 % PES	100 % WO	1.layer: 100 % CV, 2.layer: Outlast: Acryl with PCMs	100 % WS	100 % CV

CO - cotton, PES - polyester, WO - wool, PA - polyamide, EL - elastane, PCMs - phase change materials, CV - viscose, WS - Kashmir

*Experimental protocol and environmental conditions*

All tests with wear trials were performed under artificially created environmental conditions in a climatic chamber at a constant air movement of  $0.2 \text{ ms}^{-1}$  and at different cold environmental temperatures from  $10 \text{ }^\circ\text{C}$  till  $0 \text{ }^\circ\text{C}$  with step of  $5 \text{ }^\circ\text{C}$ , and 50 % relative humidity. The experimental protocol was approved by the Slovenian Ethic Committee - *Komisija Republike Slovenije za medicinsko etiko* (12.02.2008). Figure 1 shows participant with experimental clothing system in a climatic chamber during test protocol. Participants (test persons) followed an exercise protocol for 110 minutes, consisting of five period activities:

1. Activity (A1) - a 20 minutes rest on a chair (preconditioning) at  $20\text{-}23 \text{ }^\circ\text{C}$  and around 50 % RH.
2. Activity (A2) - 20 minutes of sitting on a chair in a climate chamber at an ambient temperature from  $10 \text{ }^\circ\text{C}$  till  $0 \text{ }^\circ\text{C}$  (with step of  $5 \text{ }^\circ\text{C}$ ) and 50 % RH.
3. Activity (A3) - 30 minutes of walking  $3.5 \text{ kmh}^{-1}$  on a treadmill in a climate chamber at an ambient temperature from  $10 \text{ }^\circ\text{C}$  till  $0 \text{ }^\circ\text{C}$  (with step of  $5 \text{ }^\circ\text{C}$ ) and 50 % RH.
4. Activity (A4) - 20 minutes of sitting on a chair in a climate chamber at an ambient temperature from  $10 \text{ }^\circ\text{C}$  till  $0 \text{ }^\circ\text{C}$  (with step of  $5 \text{ }^\circ\text{C}$ ) and 50 % RH.
5. Activity (A5): a 20 minutes rest on a chair at  $20\text{-}23 \text{ }^\circ\text{C}$  and around 50 % RH.

*Subjective assessment of the thermal comfort of clothing*

The methods for evaluating subjective assessment of thermal comfort use different scales to measure thermal sensation and comfort. There are a number of subjective scales which have been used in the assessment of thermal environments; the most common of these are the seven-point scales of ASHRAE (1966) (7).



Figure 1. Participant with experimental clothing system in a climatic chamber

Subjective assessment of thermal comfort was obtained during the experiment according to a questionnaire and an assessment scale defined by ISO 10551:2004 (5). Subjects answered at predetermined time of experiment using specially designed questionnaires; last minute of each period and second minute of next period. International standard ISO 10551:2004 (5) presents the principles and methodology for the construction and use of scales for assessing the thermal environment. Scales are divided into two types: personal and environmental. Those related to the personal thermal state may be perceptual – How do you feel now? (e.g. hot) – affective – How do you find it? (e.g. comfortable) – and preference – How would you prefer to be? (e.g. warmer). Those related to the environment fall into two types: acceptance – Is the environment acceptable?, and tolerance – Is the environment tolerable? (5, 7). When determining the subject's thermal perception, the test subjects assessed the perceptual judgements of personal thermal state according to a scale from +4, which means that they felt very hot, up to a scale -4, which means that they felt very cold. The test subjects assessed the "affective" thermal comfort according to a scale from 0, which means that they felt thermally comfortable, up to a scale +4, which means that they felt extremely uncomfortable. In determining the desired thermal state, the test subjects have provided an evaluation of the desired thermal state according to a preference scale, where scale +3 means that people desire much warmer thermal state, while scale -3 means that people desire much cooler thermal state. When assessing the acceptability of the current thermal conditions, the test subjects evaluated the current thermal environment as more acceptable (degree 0) and more unacceptable (degree 1). By judging the personal tolerance of the thermal environment, the test subjects determined whether they excellently tolerate the current thermal situation (degree 0), or they can't stand it any longer (degree 4) (5).

## RESULTS AND DISCUSSION

The results of this research into the feeling of thermal comfort are presented as an analysis of the impact of cold environmental conditions on the subject's thermal perception and "affective" assessment of thermal comfort whilst wearing different business clothing systems made of both conventional textiles and textiles in combination with PCMs. Figure 2. shows the results of the mean subjective ratings of the perceptual judgements of personal thermal state (thermal perception), while Figure 3. shows the results of the mean subjective ratings of the evaluative judgements of personal thermal state (subjective assessment of thermal comfort) evaluated when wearing different clothing systems in a cold environment with ambient temperatures of 10 °C, 5 °C and 0 °C.

The results of the subjective evaluation of the perception of the personal thermal state analyzed in a cold environment (Figure 2) show that when the test subjects were wearing clothing systems at an ambient temperature of 10 °C they felt neutral (degree 0) or slightly cool (degree -1) in spite of lower mean skin temperatures (around 32.0 °C) measured during the trials (8). The results also show that after walking (in 72<sup>nd</sup> minute) when the test subjects were wearing clothing system cs9 (male suit made of 68 % Acryl with Outlast PCMs, 28 % WO, 4 % EL) they felt slightly warm, whereas while wearing other clothing systems they felt neutral.

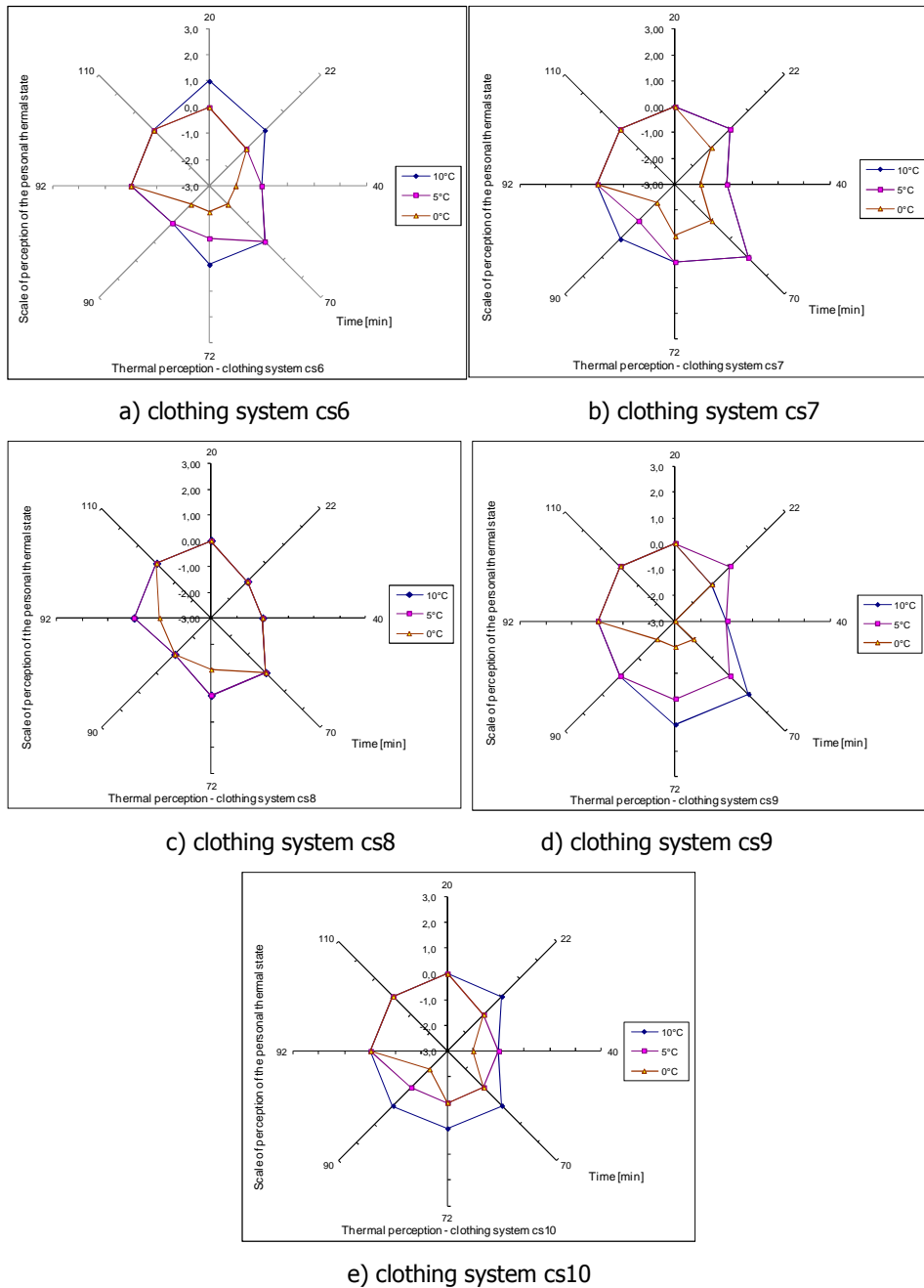


Figure 2: The effect of ambient temperature on the perception of the personal thermal state when wearing different clothing systems in a cold environment at ambient temperatures of 10 °C, 5 °C and 0 °C

From the results of mean skin temperatures (8) it is evident that after walking when wearing clothing system cs9 the mean skin temperature again rises up to 32.0 °C. This is where the biggest rise is noted (8). It is also evident from the results that, after 20 minutes of resting (in 90<sup>th</sup> minute) the test subjects mostly felt neutral (in clothing systems cs7, cs9 and cs10) or slightly cool (in clothing systems cs6 and cs8). It can be seen from the results that, when wearing clothing systems at an ambient temperature of 5 °C after 20 minutes of sitting in a climate chamber, the test subjects mostly felt slightly cool. The results also show that in spite of lower mean skin temperatures (lower than 31.0 °C), measured during the wear trials (8) in between walking, the test subjects felt slightly cool or even neutral. After 20 minutes of resting (in 90<sup>th</sup> minute) the test subjects felt slightly cool or even neutral (in clothing system cs9 with PCMs). The results also show that, at an ambient temperature of 0 °C, the test subjects mostly felt cool (degree -2) or slightly cool (degree -1) in spite of lower mean skin temperatures (between 30.0 °C and 32.0 °C) measured during the wear trials (8). It is evident from the results that the test subjects, after 20 minutes of resting in a climate chamber, mostly felt cool, except in clothing system cs9, where test subjects felt cold (degree -3). In spite of very low mean skin temperatures (around 30.0 °C) measured during the wear trials (8) between walking, the test subjects felt cool or slightly cool, while in clothing system cs9 they still felt cold. It is also evident that, after 20 minutes of resting (in 90<sup>th</sup> minute) the test subjects largely felt cool, except in clothing system cs8, where they felt slightly cool.

The results of the subjective evaluation of the feeling (affective assessment) of thermal comfort (Figure 3) show that the test subjects, when wearing clothing systems at an ambient temperature of 10 °C, felt thermally comfortable (degree 0). It is evident from the results that after walking (in 70<sup>th</sup> minute), when wearing clothing system cs10 (male

suit with PCMs lining), the test subjects felt slightly uncomfortable (degree 1), but two minutes later they felt comfortable. The results of mean skin temperatures (8) show that mean skin temperature measured during walking in clothing system cs10 reduces the least (for 0.7 °C), although in the first and second activity it was the lowest, on average. It is also evident that when wearing clothing system cs6 while sitting in a climate chamber (in 40<sup>th</sup> minute), the test subjects felt slightly uncomfortable and cool. It can be seen from the results of the wear trials (8) that, when wearing clothing system cs6, the mean skin temperature at the end of second activity during sitting decreased by about 1.1 °C, while with clothing system cs10 it decreased by 0.8 °C.

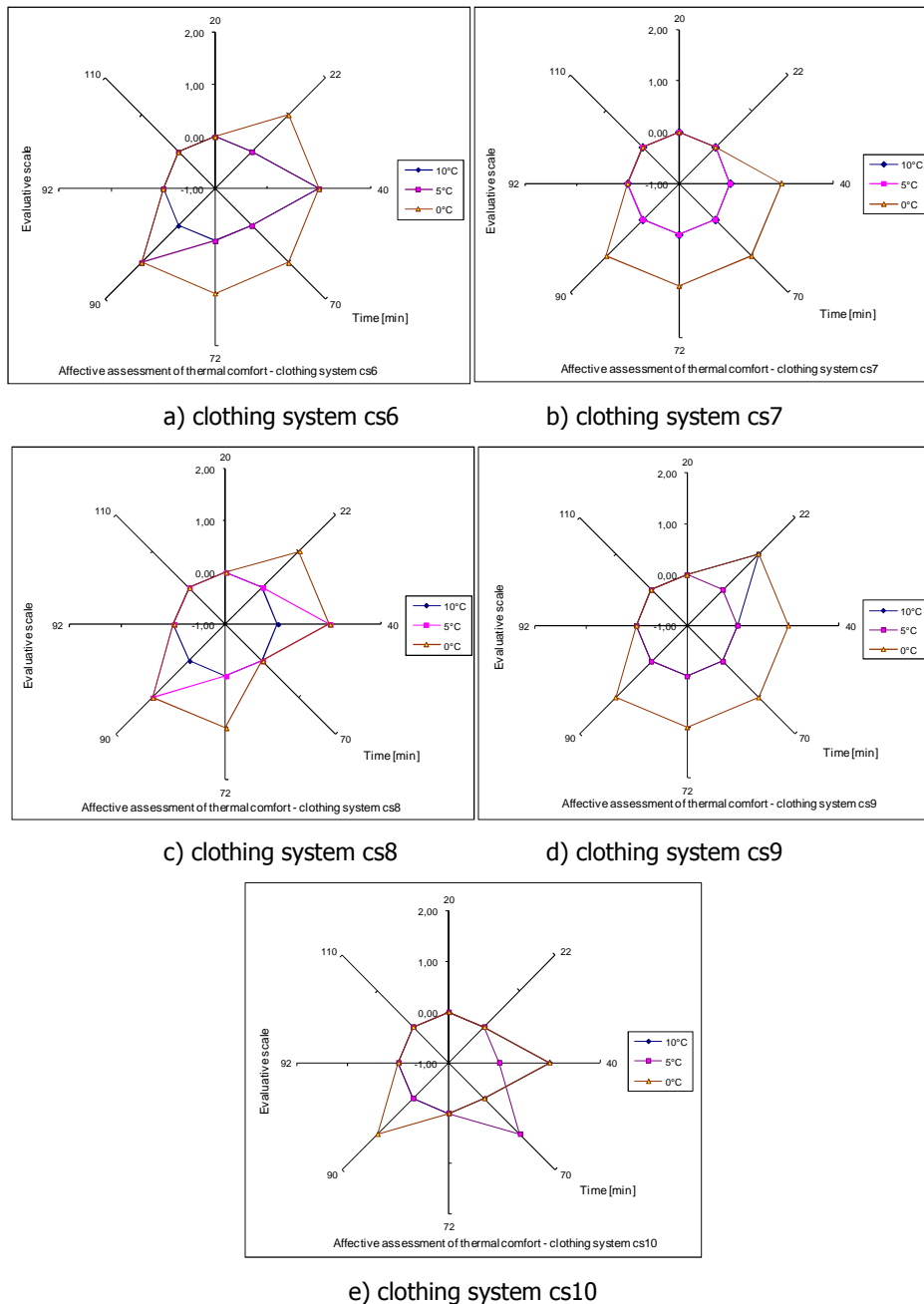


Figure 3: The effect of ambient temperature on the subjective assessment of thermal comfort when wearing different clothing systems in a cold environment at ambient temperatures of 10 °C, 5 °C and 0 °C

At the ambient temperature of 5 °C the test subjects wearing clothing system cs6 and cs8 felt comfortable when entering the climatic chamber, but after 20 minutes of sitting they felt slightly uncomfortable and cool. In spite of lower mean skin temperatures measured in the wear trials (8) between walking, the test subjects mostly felt comfortable or slightly uncomfortable in clothing system cs10. It is also evident from the results that, after 20 minutes of resting (in 90<sup>th</sup> minute), the test subjects felt comfortable or slightly uncomfortable but cool. At an ambient temperature of 0 °C when the test subjects entered the climatic chamber they felt slightly uncomfortable but still cool. After 20 minutes of sitting in the climate chamber, and also after walking, the test subjects mostly felt slightly uncomfortable because they were cold. We also noted from the results (8) that the measured mean skin temperatures after walking at 0 °C were lower than 31.0 °C, and while walking even lower than 30.0 °C. Moreover, it is also evident

from the results that the test subjects, after 20 minutes of resting (in 90<sup>th</sup> minute), felt slightly uncomfortable because they were cold. In spite of lower mean skin temperatures measured during the wear trials (8) while walking, the test subjects felt comfortable when wearing clothing system cs10 (male suit with PCMs lining). It was also noted from the results (8) that the highest mean skin temperature measured before and between walking was reached in clothing system cs10. This means that in spite of lower mean skin temperatures measured with trials at an ambient temperature of 0 °C, clothing system cs10 assures a little higher mean skin temperature during activity changes. The results obtained, as well as the subjective evaluation of thermal comfort, indicate that the clothing systems with a coat are not suitable for wearing below an ambient temperature of 0 °C, because the test subjects felt uncomfortable and the measured mean skin temperatures were lower than 32.0 °C (8), which is the lower comfort limit in a cold environment (below 32.0 °C to 29.5 °C) (1).

## CONCLUSION

The analysis of the subjective evaluation of the thermal comfort of male business clothing systems, evaluated through wear trials, shows that environmental conditions, as well as the clothing systems, have a considerable impact on the feeling of thermal comfort in a cold environment. From the subjective evaluation of thermal comfort it can be seen that, despite lower mean skin temperatures (around 32.0 °C), the test subjects, at an ambient temperature of 10 °C, felt thermally comfortable. At an ambient temperature of 5 °C, the test subjects felt somewhat uncomfortable, but during walking they could be thermally comfortable or just slightly cold, in spite of lower mean skin temperatures (around 31.0 °C) being recorded during the wear trials (8). It is also evident that the analysed clothing systems are not suitable for wearing below an ambient temperature of 0 °C, because the test subjects felt uncomfortable and the recorded mean skin temperatures were lower than 32.0 °C (8), which represents the lower comfort limit in a cold environment (below 32.0 °C to 29.5 °C) (1). This means that the clothing systems tested do not guarantee appropriate thermal protection below an ambient temperature of 0 °C. Therefore, an extra layer of lining with quilted cotton (e.g. wadding) is recommended when developing new clothing systems for cold environments. In summary, we can conclude that the subjective evaluation of thermal comfort is one of the parameters which, in combination with physiological parameters of thermo-physiological comfort, serve as very important information for forming and understanding of the personal thermal comfort of clothing in different environmental conditions.

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## SUBJEKTIVNE PROCENE TOPLOTNE UDOBNOSTI ODEĆE U HLADNOJ OKOLINI

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*Ovaj rad predstavlja studiju o subjektivnim procenama toplotne udobnosti prilikom nošenja muškog poslovnog odela, koje je izrađeno iz konvencionalnog tekstila kao što su vuna i mješavine sa vunom i tekstila u kombinaciji sa fazno promenljivim materijalima (PCMS), koje su zasnovane na znanju, da obezbede adekvatni termalni komfort korisnika odeće. Evaluacija toplotne udobnosti izvršena je na osnovi procene subjektivnog osećaja toplotne ugodnosti prilikom nošenja odeće u hladnom okruženju na temperaturi okoline od 10 °C, 5 °C i 0 °C. Kod pronalazenja subjektivnih osjećaja toplotne udobnosti prilikom nošenja odjeće, ispitne osobe su promatrane u određenoj tjelesnoj aktivnosti (sjedenje i hodanje po pokretnoj traci) u različitim klimatskim uvjetima toplotnog okruženja, u kompjutersko kontroliranoj klima komori topline, koje su procjenjivale toplotni osjećaj na bazi pitanja i stupnjevane ljestvice u skladu sa standardom ISO 10551:2004. U tu svrhu, analiza subjektivnih procjena toplotne udobnosti, toplotnog osjećaja, zelenog toplotnog stanja, prihvatljivost sadašnjih termičkih uslova i lične tolerancije životne sredine u pojedinim intervalima istraživanja bila je urađena. Rezultati su pokazali da su izražene subjektivne procene toplotne udobnosti direktno zavisne od stvarnih klimatskih uslova, kao i odeća. Utvrđeno je, da se ispitanici, uprkos zabeleženim niskim temperaturama kože, osećaju najprijetnije u izabranoj odeći na temperaturi vazduha od 10 °C. U isto vreme se utvrdi, da analizirani odećni sistemi nisu pogodni, da se nose na hladnoj temperaturi okoline ispod 0 °C, jer su se ispitanici u odeći osećali neprijatno.*

**Ključne reči:** *toplotni komfort, subjektivne procene, fazno promenljivi materijali (PCMS), odeća, hladna okolina.*

*Rad primljen: 02. 04. 2014.*

*Rad prihvaćen: 28. 07. 2014.*

