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DEPENDENCE OF THERMAL CONDUCTIVITY AND HEAT RETENTION ABILITY OF FABRICS FROM DIGITAL PRINT PARAMETERS

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Abstract: *The human body transforms the chemical energy of the food into the work and the heat through the process of metabolism. The produced heat through the skin is transferred to the environment. In this case, in the state of thermal equilibrium, the amount of heat produced is equal to the amount of heat lost by conduction, convection, radiation, evaporation and breathing. The process of conduction of heat is transferred from the body to the environment, through layers of clothing and air, with the person standing still. Conductivity of heat in clothes depends on the thermal conductivity of the fibers from which the clothes are made, the conductivity of the air trapped in the pores of the clothes and the air on the surface of the clothing, the surface of the clothing layer through which the heat and the thickness of the clothes pass. The amount of heat transferred by conduction is usually negligible because the clothing, by its characteristics, slows down heat transfer in this way. Additionally, ink layers made in printing process significantly affect the properties of textile materials and clothes made from these materials. And today textile materials are increasingly being subjected to the process of printing due to aesthetic requirements of the people. This paper investigates the influence of digital printing parameters on the thermo-physiological features of textile materials. The essential print parameter was a different number of passes. In this research were used textile fabric materials of 100% cotton fibers. With printing process parameters, such as number of passes in the print, it is possible to influence the amount of ink that is applied on and in printed material, and thus the achievement of desired values of thermal parameters of printed materials. The influence of print parameters to thermo-physiological properties of the material is evaluated through a thermal conductivity and heat retention ability. Results of the research demonstrated that, in addition to material composition, the printing process with its parameters have a significant influence on the thermo-physiological characteristics of textile materials. The values of the thermal conductivity of the printed samples show that the increase in the number of application of ink in the printing results in a rise in the value of thermal conductivity coefficient, and decrease in heat retention ability value.*

Key words: digital printing, textile materials, fabrics, thermal conductivity, heat retention ability

1. INTRODUCTION

Nowadays, from selected clothes is expected to satisfy aesthetic and fashionable requirements (Mecheels, 1992). Printing clothes makes aesthetic value of product more individual and fashionable. From technical aspect, process of printing clothes can be defined as process of transferring ink on textile substrate (Kašiković et al, 2014).
Currently the world's annual print of textile material is between 11 and 13%, that is more than 27 billion m^2 of textile substrates, with annual growth rate of 2% (Momin, 2008; Provost, 2009; Onar et al, 2012). The value of textile material printing industry in 2010 was 165 billion US$. Textile material printing industry is under great pressure of constant changes. This market is seasonal and highly dependent on fashion trends (Gupta, 2001). Demands of customers are changing very fast, therefore the collections are changing frequently in two months (Özgüney et al, 2007). Trends on market, like: decrease in circulation, demands for higher print quality, rapid job change and short deadlines, unique and personalized print, have led to increased interest for digital printing in textile material printing (Kanik et al, 2004; Mikuž et al, 2005; Stančić et al, 2013). Digital printing efficiency, as flexible way of ink transfer on substrate in the form of a desirable design, is primarily reflected in respect of costs and time needed for production of smaller circulations (Novaković et al, 2010). Besides that, digital printing technique enables faster response to market demands and mass individualization.
More important, for clothes, is to meet the ergonomic and physiological requirements (Mecheels, 1992). Does clothing meet aesthetic and ergonomic demands customer easily evaluates before or during first

wearing. With physiological function it is different, and clothing with good physiological characteristics should make man does not feel heat or cold in different climatic conditions (Mecheels et al, 1976). Comfort is basic and universal need of human being and presents one of the most important aspects of clothing. During clothes wearing, heat and humidity produced by body has been stopped as layers of air before passing in the environment, resulting in characteristic microclimate between skin and clothing, defined as the feeling of comfort (Yoo et al, 2000; Grujić et al, 2010). Thermal effects largely contribute to the comfort of the individual, whereby a complex physiological and psychological factors together with clothes play an important role in defining the complex phenomenon of comfort (Andreen et al, 1953).
Human body with the process of metabolism constantly transforms food chemical energy into work and heat. Produced heat is transferred through skin and further through clothing system to the environment. Heat exchange processes in dressed and undressed human are qualitatively equal, while quantitatively depend on the thermodynamic properties of clothing, which presents separating surface between body and environment (Mecheels, 1991; Grujić, 2010). The process of heat exchange between body and environment itself is done by processes of: conduction, convection, radiation, evaporation and respiration (Stoecker et al, 1982). Greatest part of heat exchange is done by the process of convection. With this process heat is transferred by the movement of gas or liquid. Quantity of heat lost by the convection is determined with difference between temperature of clothing surface and air, and also with convective heat transfer coefficient, which is, in turn, determined with speed of air movement through clothing system (Persons, 2003). The physiological properties of clothing, and thus wearing comfort, could be expressed, apropos quantified, through heat and sorption properties of material (Huang, 2006; Das et al, 2007).
Previous research showed that thermal conductivity and heat retention ability of textile material is conditioned by structural properties of material. However, during printing process layer of ink is transferred on clothing. Part of printed ink covers clothing surface, while other part of ink fills pores between fibers in yarn. Thereby, printed ink presents new layer of material, actually additional barrier for the movement of air through the clothing. In order to get new scientific knowledge, this study examined influence of printing process, as one of the methods for increasing visual attractiveness of clothes, on physiological comfort of printed textile materials. Thereby was examined influence of digital ink-jet printing parameters and number of ink layers, on thermal conductivity and heat retention ability of cotton fabrics.

2. METHODS AND MATERIALS

Research of printing process influence on thermal conductivity and heat retention ability of fabric was performed on purpose-made fabric. Basic characteristics of examined fabric are shown in Table 1.

Table 1: Characteristics of material used in research

Sample	Material type	Type of weaves	Material composition (%)	Fabric weight (g/m^2)	Thread count (cm^{-1})
T-A	Fabrics	Single	Cotton 100 %	177,68	Vertical: Dv = 20 Horizontal: Dh = 20
Method			ISO 1833-1	ISO 3801	ISO 7211-2

For research purposes special test image has been developed. Test image was created using Adobe Illustrator CS5 software application, and was consisted of twelwe patches dimension 20 x 20 cm, and coverage of 10%, 50% and 100% tonal values (TV) of yellow process color.
Printing of samples was done using ink-jet printing system Polyprint TexJet. Samples were printed with one, three and five ink applications, without intermediate drying in case of printing with more ink applications. Printing of samples has been done with resolution of 720 x 720 dpi, using water-based pigment colors DuPont Artistri Pigment- 5000 Series (yellow). After printing process, prints were exposed to drying process and fixation of printed inks. Samples were dryed with heat effect at a temperature of 130 °C for 120 seconds, using device for drying imprints tp 4040s from manufacturer „Opremakv“.
Before laboratory measurements samples were air-conditioned for 24 hours at standard atmosphere (temperature of 20 °C and relative air humidity 60%). In order to achieve higher accuracy of the measurement results, more samples were measured with repetition on the individual samples. As measurement results were taken arithemtic means of ten times measured numerical values.

Heat conductivity is one of the criteria for the insulation properties of textile fabrics. Since all textile fibers, except glass-fibers, conduct heat better than air, the thermal insulation does not only depend on the specific conductivity of the material used but also of the air volume, which is contained in the textile material, i.e. of the structure and thickness of the textile material. (Grujić, 2010).
Heat conductivity measurement is based on the heat transfer from the warmer to the colder, i.e. on the principles of heat conduction. To measure the heat conductivity coefficient, a BT measurement medium with a heat source heated to 35 °C and a metered body with water VT is used. When measuring the sample, it is placed on the measuring body with water VT. When the temperature of the BT metering unit reaches a default value of 35 °C, the BT measurement body is placed face-up on the sample. The value of the heat flow ϕ is evident on the digital display of the device.
These values of the heat flow are used to calculate the thermal conductivity coefficient or thermal conductivity coefficient according to the expression (1) (Kato Tech Co. Ltd., 1998):

$$\lambda = \frac{\phi \cdot h}{A \cdot (T_{BT} - T_a)} \quad (1)$$

where:

- λ – coefficient of thermal conductivity [W/mK],
- A – surface of BT unit [0,0025 m^2],
- h – thickness of material [m],
- T_{BT} – temperature of BT unit [K],
- T_a – temperature of room [K],
- ϕ – heat flow [W].

Heat retention or thermal insulation is greatest when the man is stationary, because then the air under the clothes is still. Determination of heat retention of the test materials, i.e. heat flow measurement, was performed with larger BT measuring unit, which is located in an anvil and heated to a temperature of 35 °C. At that time, the wind was constantly moving at a velocity of 1 ms^{-1} at a temperature of 20 °C ± 2 °C. Constant movement of the air is achieved using the fan. The loss of heat or heat flow can be determined by the following methods: dry contact method, dry contactless method, wet contact method, wet contactless method. In determining the heat resistance of textile materials, a dry contactless method was used. From the heat flow values obtained, the heat retention of the textile materials is determined according to the expression (2) (Kato Tech Co. Ltd., 1998):

$$Rc = \frac{(Ts - Ta) \cdot A}{Hct} \quad (2)$$

where:

- Rc – heat retention of textile [m^2K/W],
- Hct – dry heat flow, that goes throught material [W],
- A – surface of BT unit [m^2],
- T*s* – temperature of BT unit (skin temperature) [°C],
- T*a* – temperature of air in anvil (air temperature) [°C].

3. RESULTS AND DISCUSSION

Results of thermal conductivity of printed cotton fabrics research are shown in Figure 1. The results indicate that the increase of the number of ink layers applied results in an increase in the coefficient of thermal conductivity of printed cotton fabrics. By observing the value, it can be noticed that applying of the ink nearly doubles values of thermal conductivity coefficients of unprinted cotton fabrics. Figure 1 also shows that by increasing the tone value, the value of the coefficient of thermal conductivity increases, irrespective of whether the samples are printed with one, three or five ink layers. It can be noted that the increase of the coefficient of thermal conductivity is higher with the increase of the tone value and that the coefficient of thermal conductivity of three ink layers on 10% and 50% is similar to coefficient of thermal conductivity of 50% and 100% on samples with one ink layer respectively.

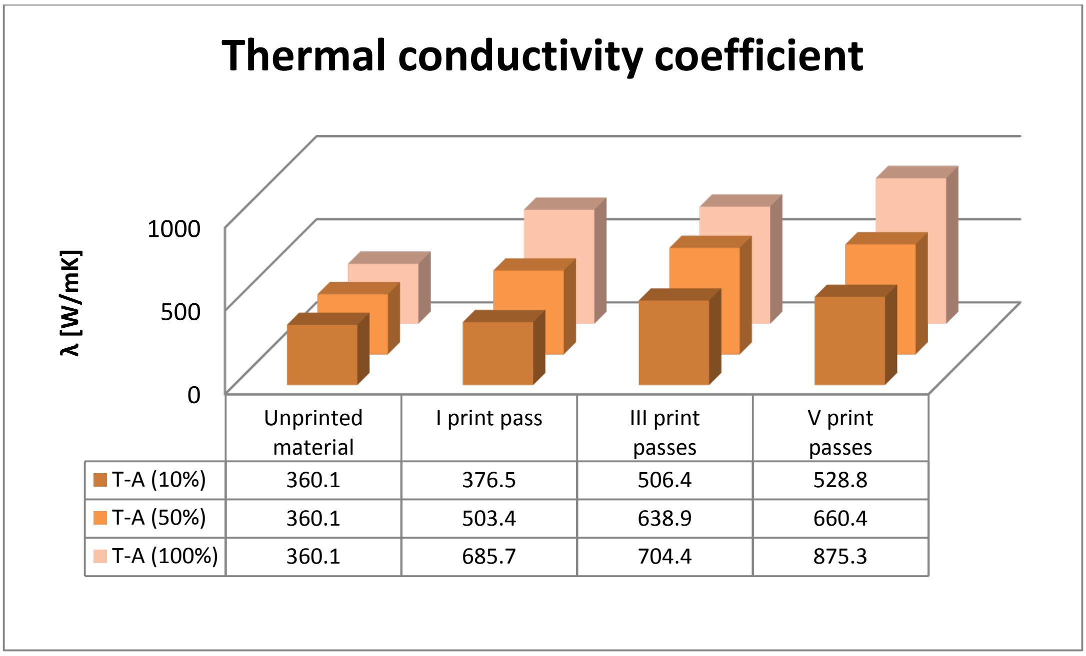

Figure 1: Thermal conductivity value of printed cotton fabrics

With research results analysis were obtained statistically reliable dependences of thermal conductivity on number of ink layers, which are presented in Table 2.

Table 2: Statistical analysis of thermal conductivity values of printed cotton fabrics

λ = 315,678 + 3,159 · TV + 41,575 · IL										
Multiple reg. coef.	Std. Error of the Estimate	b_o = 315,678			b_1 = 3,159			b_2 = 41,575		
R^2	s	Std. Error	t	p	Std. Error	t	p	Std. Error	t	p
0,951	3,740,589	31,724	9,951	0,000069	0,339	9,327	0,000086	7,635	5,445	0,002
λ - Thermal conductivity coefficient TV – tone value IL – ink layers										

Results of heat retention of printed cotton fabrics research are shown in Figure 2. The results indicate that the increase of the number of ink layers applied results in a decrease of the heat retention of printed cotton fabrics. By observing the value, it can be noticed that by increasing the tone value, the value of the heat retention decreases, irrespective of whether the samples are printed with one, three or five ink layers. It can be noted that the decrease of the heat retention is lower with the increase of the tone value.

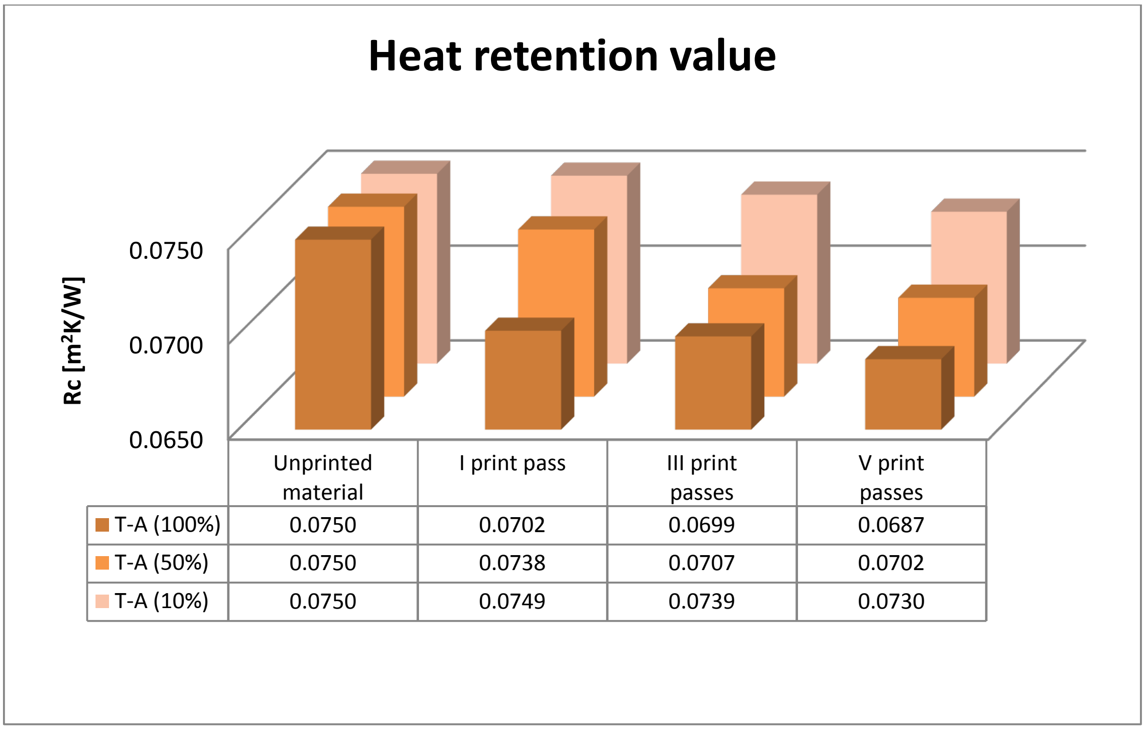

Figure 2: Heat retention value of printed cotton fabrics

With research results analysis were obtained statistically reliable dependences of heat retention on number of ink layers, which are presented in Table 3.

Table 3: Statistical analysis of heat retention values of printed cotton fabrics

Rc = 0,076 - 0,000048 · TV - 0,001· IL										
Multiple reg. coef.	Std. Error of the Estimate	b_o = 3598,109			b_1 = -7,110			b_2 = -140,333		
R^2	s	Std. Error	t	p	Std. Error	t	p	Std. Error	t	p
0,886	152,640	129,453	27,795	$1{,}4345 \cdot 10^{-7}$	1,382	-5,145	0,002	31,158	-4,504	0,004
Rc – Heat retention value TV – tone value IL – ink layers										

4. CONCLUSIONS

In the presented research, influence of digital ink-jet printing process parameters on sorption properties of printed clothes, apropos on parameters of physiological comfort of printed clothes was tested. In that purpose, dependence of thermal conductivity and heat retention of printed cotton fabrics on variable factors of printing process was tested, i.e. from different tonal coverage and different number of ink layers. Measured values of thermal conductivity for tested fabrics behave in a manner that with increasing the number of ink layers in printing, and also increasing the tonal coverage, leads to thermal conductivity value increase. Measured values of heat retention for tested fabrics behave in a manner that with increasing the number of ink layers in printing, and also increasing the tonal coverage, leads to heat retention value decrease. Also, based on experimentally obtained results mathematical dependence models of thermal conductivity on printing parameters were created. These models could be used in real production conditions, during printing clothes made from these materials, and in order to adjust printing process parameters to get clothes for different purpose, with optimal both aesthetic and sorption properties, and all of that in order to get clothes with optimal comfort properties.

With printing process part of printing ink is transferred on material surface, and other part penetrates the interior of material and fills pores between yarn as well as pores between fibers. In this way in textile material is created additional barrier, which disturbs the free passage of air through textile material. Increasing the value of thermal conductivity and decreasing the value of heat retention by increasing tonal coverage and number of ink layers in printing is explained by the fact that increasing of these parameters leads to application of larger amount of ink on and in printed material. This leads to covering the larger quantity of fibers, and thus to reducing possibilities for free passage of air through textile material.
Measured values of thermal conductivity also show that closely equal values of thermal conductivity can be obtained with combination of number of ink layers and tone value. This fact is, in turn, important from an economic point of view, because it shows that similar values of sorption parameters can be obtained with smaller number of ink layers in printing by increasing tone value. In this way it is possible to achieve an increase in productivity, because time needed for printing process is being reduced, without affecting the values of sorption properties of printed cotton fabrics, and also the comfort of the clothes made from these materials.
Summarizing the results of the research it can be concluded that printing parameters have great influence on thermal conductivity and heat retention. In order to obtain further knowledge, in future research it is planned to test the impact of materials of different composition. Also, done research should be carried out, besides fabrics, on knitwear.

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