Analysis of heat transfer and factors affecting the thermal properties on rib 1x1 knitwear

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ABSTRACT – REZUMAT

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Clothing comfort is very important feature which is considered as a result of different process of heat exchange between human body, clothing and environment. The purpose of this paper is to analyse the impact of clothing insulation on the heat transfer. The measurements were carried out on commercially 1x1 RIB knitted fabrics used for the production of next-to-skin shirts. The one group of samples are made from 100% cotton yarn and another with 96% cotton and 4% lycra. It is noticed that knitted material composition affected the change in heat resistance. Also, this paper presents and verifies the correlation between the measured values of thermal resistance (Rct) and the knitwear thickness (dpl), the covering factor (K), the porosity of the twists (ε) and the surface coefficient (δ_p). Based on these results, a mathematical model for calculating thermal resistance is proposed. Comparing the results obtained with the proposed equation and the measured results, we can see that the deviations are minimal. The highest deviation for sample C4 is 0.05%, while the largest deviation for sample CL4 is 4.6%.

Keywords: *RIB knitwear, heat transfer, thermal resistance, porosity, tightness factor, surface coefficient*

Analiza transferului de căldură și a factorilor care influențează proprietățile termice ale tricoturilor patent 1x1

Confortul vestimentar este o caracteristică foarte importantă, care este luată în considerare ca urmare a unui proces de schimb de căldură între corpul uman, îmbrăcăminte și mediu. Scopul acestei lucrări este de a analiza impactul izolației produselor de îmbrăcăminte asupra transferului de căldură. Măsurătorile au fost efectuate pe tricoturi patent 1x1 pentru producerea bluzelor care intră în contact direct cu pielea. Un grup de probe este realizat din 100% fire de bumbac și altul cu 96% bumbac și 4% lycra. Se observă că, compoziția tricotului influențează rezistența termică. De asemenea, această lucrare prezintă și verifică corelația dintre valorile măsurate ale rezistenței termice (Rct) și grosimea tricotului (dpl), factorul de acoperire (K), porozitatea (ε) și coeficientul de suprafață (δ_p). Pe baza acestor rezultate, este propus un model matematic pentru calcularea rezistenței termice. Comparând rezultatele obținute cu ecuația propusă și rezultatele măsurate, putem observa că abaterile sunt minime. Cea mai mare abatere pentru eșantionul C4 este de 0,05%, în timp ce cea mai mare abatere pentru eșantionul CL4 este de 4,6%.

Cuvinte-cheie: *tricot patent, transfer de căldură, rezistență termică, porozitate, factor de etanșeitate, coeficient de suprafață*

INTRODUCTION

Technological and scientific development largely enabled manufacturing of high quality textile products. In order to successfully participate in market competition, many manufacturers today are investing significant resources in research and development of products tailored to the needs of man. Clothing wear comfort is one of the key factors during the clothes selection, and a decisive factor in the evaluation of the clothing quality. The garments can be seen as a heat exchange layer between the body and its environment, and contemporary requirements regarding clothing comfort are much higher than in the past [1].

Thermal comfort, which is an important factor when designing a garment, is closely linked to the behaviour of heat transfer in clothes [2]. Thermo-physiological comfort is directly related to physiological processes of human body and is the result of the balanced process of heat exchange between the human body, the clothing system and the environment [1].

The body's heat control centre is located in the brain and regulates the transmission of heat by the flow of blood through blood vessels, capillaries to the surface of the skin and the sweat secretion. In order to control the heat exchange, we can protect the body against overheating as well as against freezing. In this case, physical regulation controls heat exchange, and chemical regulation controls thermal processes. The body is heated with thermal energy that is obtained from the energy from the degradation of the molecule, and fats. Heat transfer can occur by radiation R, convection C, conduction K, evaporation E, and respiration Eres (figure 1) [3, 4].

Radiation heat transfer occurs constantly between the body and the environment in which the body resides, i.e. in both directions, depending on the difference in body temperature of the skin and the temperature of other surfaces. The average heat loss by radiation varies, and in moderate climatic reactions can range from 40 to 60%. Convection is the process of losing heat by moving air or water molecules through the skin [5]. The higher the speed of air movement, the greater the temperature difference between the body and the surrounding air, and the larger the surface area of the body, the greater the degree of heat transfer. If the air temperature is lower than the skin (and clothing) temperature, the heat convection is positive and the temperature is released from the body to the environment. If the air is warmer than the skin temperature, the heat convection is negative and the body receives heat from the air. Convection becomes more and more effective in removing heat as air temperature drops and air movement increases [6].

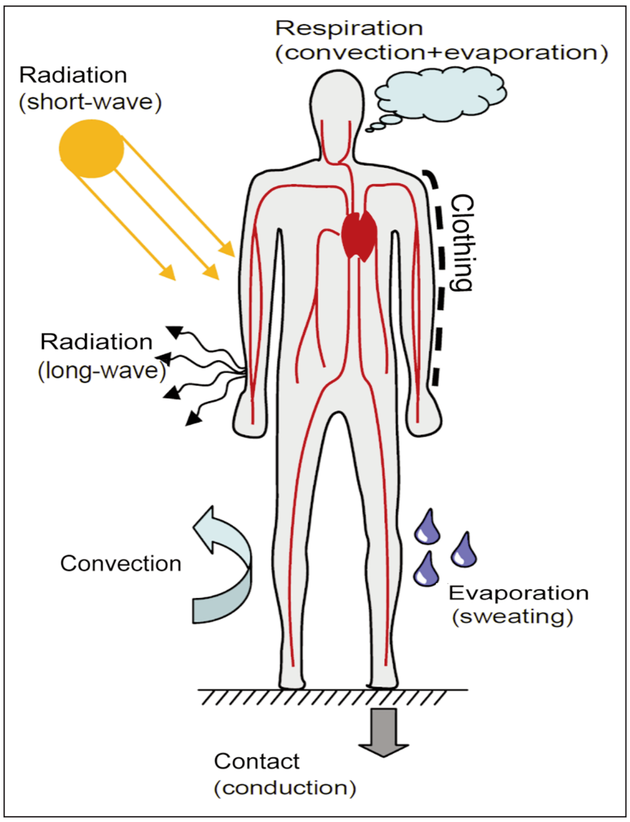


Fig. 1. Heat transfer over the human body [4]

Under normal conditions, about 30% of heat is exchanged by this type of heat transfer between the body and the environment. The amount of heat transmitted by conduction is much smaller than the amount transmitted by convection and it is essential when people are in contact with cold objects [7]. The exchange of heat by conduction is 15% of the total heat transfer, primarily depends on the subject and the material that is in contact with the skin [8, 9]. Conductivity allows us to lose heat over the soles or body when lying or sitting on a cooler surface. Heat transfer by sweat evaporation is always present and it increases in hot environment. If environment temperature rises over a comfortable body temperature, hot skin secretes depend on moisture quantity on the skin and the difference between water vapor pressures on the skin and in environment. In a human being, evaporation is always present [10].

The thermal properties of clothing that demonstrate the ability to transfer heat and moisture from the surface of the human body to the environment are the dominant determinants of the thermal comfort of clothing. The measuring values that are related to the ability to evaluate the heat exchange of the human body with the environment, and are related with the human perception of comfort are thermal resistance or thermal insulation (*Rct*) and resistance to water vapour flow on clothing (*Ret*). The impact of clothing and air trapped in clothing and around the body can be assessed by thermal comfort properties, which provide the ability to assess the effect of clothing on thermal balance in a particular environment [1].

Thermal balance in the body is achieved by balancing the amount of heat that the body produces and the heat that the body exchanges with the environment [11]. The equation that defines the thermal balance includes three terms: a term that defines the production of heat in the body, heat transfer and accumulation [3]. The thermal balance in the body is achieved according to the following expression [11]:

$$M_0 = W + R_t + K_v + K_D + E + L_v + S \qquad (1)$$

where M_0 is the total amount of produced energy calculated from the oxygen consumption, W – external work, R_t – heat loss by radiation, K_v – heat transfer, K_D – heat guidance, E – evaporation, L_v – warming and humidification of air caused by inhalation/exhalation, S – the accumulation of heat in the body.

The comfort zone in which a person feels comfortable ranges from 20 to 23 °C. This zone depends on many factors but the most important are: type of clothing, season, diet, gender, habits, etc.

Established body temperature balance does not automatically mean good comfort, as a person may feel uncomfortably warm due to sweating or uncomfortably cold due to low skin temperatures [12].

The aim of this paper is to investigate the influence of structural characteristics (knitwear's thickness, porosity, covering factor and surface coefficient) on the thermal resistance of *Rct* in ribbed 1×1 knitwear. The effect of incorporation of elastane fibres into the knit structure on thermal resistance was also analysed. For this purpose ribbed 1×1 knitwear are made with four different densities of yarn made from 100% cotton and from a mixture of cotton/elastane yarns.

Thermal resistance (Rct)

The thermal resistance (*Rct*) is the thermal insulation of the material and is inversely proportional to the thermal conductivity, as shown by the equation [13]:

$$Rct = \frac{h}{\lambda} \; (\mathrm{m^2\,K/W}) \qquad (2)$$

In dry materials or in materials containing very little water, it depends on the thickness of the material (*h*) and the conductivity of the fibres (λ).

MATERIALS AND METHODS

Experimental part of this paper was carried out using the knitwear that is commercially used for the production of clothes of next-to-skin-wear. This kind of clothes are worn either as one-layer summer wear or as the first layer that is in contact with human skin in cooler season of the year. The knitwear samples are produced with 1×1 RIB structure. Samples are made of 100% CO yarns and CO yarns in combination with Lycra (96% CO/4% LY). Linear density of Lycra which was used is 44 dtex. CO yarn was used in four linear densities: 20 tex, 17, 14 and 12 tex. Samples in the raw state and stained samples were examined (table 1).

Knitwear is made on a circular knitting machine type Fv 2.0 of company Mayer & Cie. Characteristics of the machine are as follows: cylinder diameter 19" (inch), the gauge is E18 and with 40 feeders, the knitting speed is 1.7 m/s. All of the samples are knitted under the same conditions on the same machine.

A measuring device used to test the thermal characteristics of knitwear samples was KES FB 7 – Thermo Labo II.

The correlation analysis is used to compare the relation between the resulting values of thermal resistance (*Rct*) and the resulting values of mass per unit area (*m*), porosity (ε), surface coefficient (δ_p) and tightness factor (*K*). The correlation coefficients present the strength of the association between two variables. The coefficient of determination (R^2), was used to measure the strength of the linear association between variables. The value of coefficient of determinations ranges between –1 and 1. The positive value of coefficient of determination means that the values obtained with two methods are proportionally linear. If the coefficient of determination is +1 this presents the maximum of positive correlation. If the correlation coefficient is zero, this means zero correlation.

RESULTS AND DISCUSSION

Experimentally obtained results of mass per unit area, porosity, tightness factor and volume coefficient and thermal resistance are presented in table 2.

The correlation between the thermal resistance and mass per unit area, volume coefficient, porosity and tightness factor are shown in figures 2–9.

It can be seen from the previous considerations that there is a correlation between the parameters of knitwear and the resistance to heat transfer of the same knitwear. Therefore, a suitable mathematical model is proposed to calculate the Rct values of the ribbed knit fabric samples tested, based on the experimentally measured values of knit thickness (*dpl*), coverage factor (*K*), surface coefficient (δ_p) and porosity (ε). The coefficients for the proposed formula are shown in table 3 and figure 10 and they are given separately for 100% cotton bleached ribbed knitwear made of cotton yarns 20, 17, 14 and 12 tex, for 100% cotton ribbed coloured knitwear knitted of cotton yarns 20, 17, 14 and 12 tex, for ribbed bleached knitwear of 96% cotton and 4% lycra woven from cotton yarns of fineness 20, 17, 14 and 12 tex and for ribbed dyed fabrics of 96% cotton and 4%

Table 1

BASIC CHARACTERISTICS OF ANALYZED KNITWEAR'S SAMPLES

Sample	Structure	Fibre composition	Linear density (tex/dtex)	Twists (m^{-1})	Finishing
B_1	1×1 RIB	100% CO	20	780	bleached
B_2	1×1 RIB	100% CO	17	804	bleached
B_3	1×1 RIB	100% CO	14	929	bleached
B_4	1×1 RIB	100% CO	12	977	bleached
BL_1	1×1 RIB	96% CO/4% LY	20/44	780/0	dyed
BL_2	1×1 RIB	96% CO/4% LY	17/44	804/0	dyed
BL_3	1×1 RIB	96% CO/4% LY	14/44	929/0	dyed
BL_4	1×1 RIB	96% CO/4% LY	12/44	977/0	dyed
C_1	1×1 RIB	100% CO	20	780	bleached
C_2	1×1 RIB	100% CO	17	804	bleached
C_3	1×1 RIB	100% CO	14	929	bleached
C_4	1×1 RIB	100% CO	12	977	bleached
CL_1	1×1 RIB	96% CO/4% LY	20/44	780/0	dyed
CL_2	1×1 RIB	96% CO/4% LY	17/44	804/0	dyed
CL_3	1×1 RIB	96% CO/4% LY	14/44	929/0	dyed
CL_4	1×1 RIB	96% CO/4% LY	12/44	977/0	dyed

Table 2

EXPERIMENTALLY OBTAINED RESULTS OF MASS PER UNIT AREA, POROSITY, TIGHTNESS FACTOR AND VOLUME COEFFICIENT AND THERMAL RESISTANCE					
Sample	**Knitwear thickness d_{pl} (mm)**	**Porosity ε**	**Surface coefficient δ_p**	**Tightness factor K ($\sqrt{tex}$/cm)**	**Thermal resistance R_{ct} (m^2Kw^{-1})**
B_1	1.073	0.88	1.16	15.8	0.0726
B_2	1.062	0.89	1.23	14.4	0.0745
B_3	0.965	0.91	1.32	13.4	0.0772
B_4	0.914	0.92	1.40	12.4	0.0786
BL_1	1.217	0.85	0.84	15.9	0.0676
BL_2	1.171	0.86	0.90	14.6	0.0705
BL_3	1.205	0.89	0.92	13.2	0.0719
BL_4	1.164	0.89	0.96	12.2	0.0768
C_1	1.116	0.87	1.16	15.7	0.0711
C_2	1.036	0.89	1.11	14.4	0.0737
C_3	1.002	0.91	1.31	13.5	0.0763
C_4	0.920	0.91	1.38	12.5	0.0785
CL_1	1.225	0.85	0.86	15.9	0.0654
CL_2	1.228	0.87	0.86	14.5	0.0675
CL_3	1.196	0.88	0.93	13.0	0.07
CL_4	1.158	0.89	0.96	12.1	0.0774

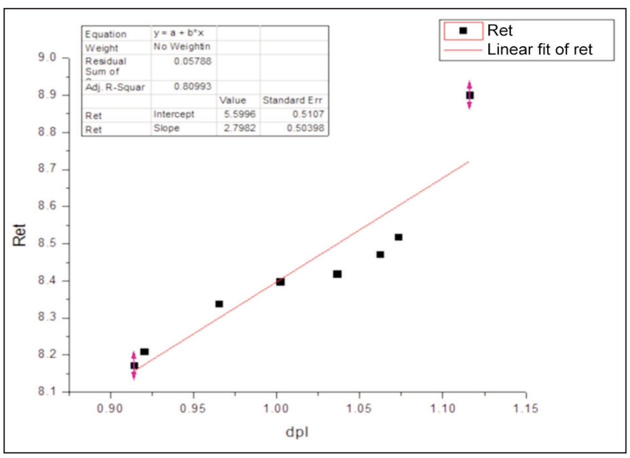


Fig. 2. Relationship between Rct and mass in 100% CO bleached and dyed knitwear, $R^2 = 0.8099$

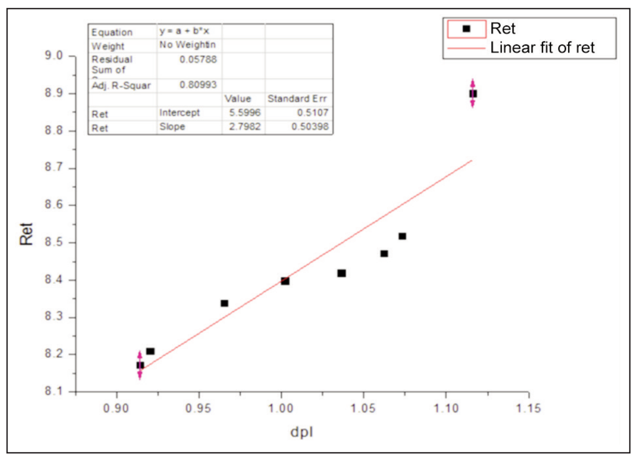


Fig. 3. Relationship between Rct and mass in 96% CO/4% LY bleached and dyed knitwear, $R^2 = 0.9675$

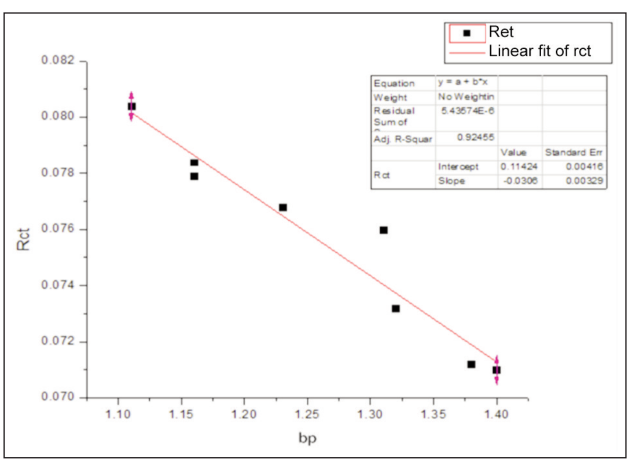


Fig. 4. Relationship between Rct and δ_p in 100% CO bleached and dyed knitwear, $R^2 = 0.92455$

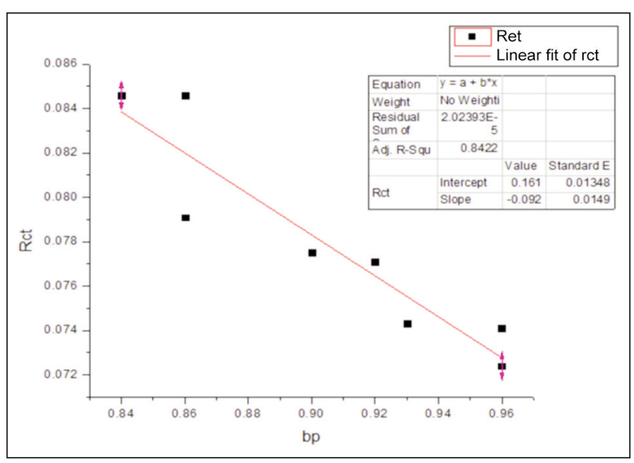
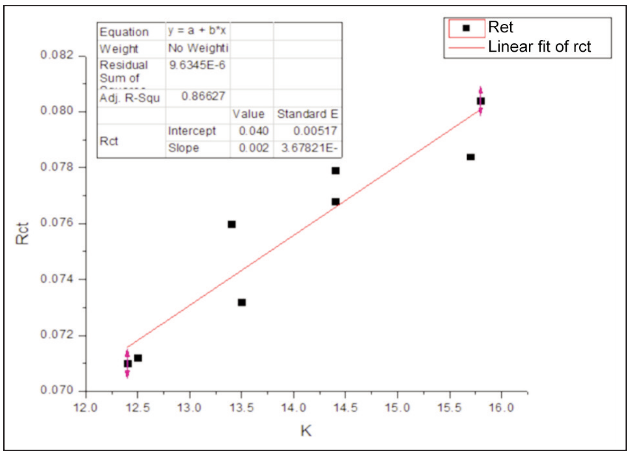


Fig. 5. Relationship between Rct and δ_p in 96% CO/4% LY bleached and dyed knitwear, $R^2 = 0.8422$



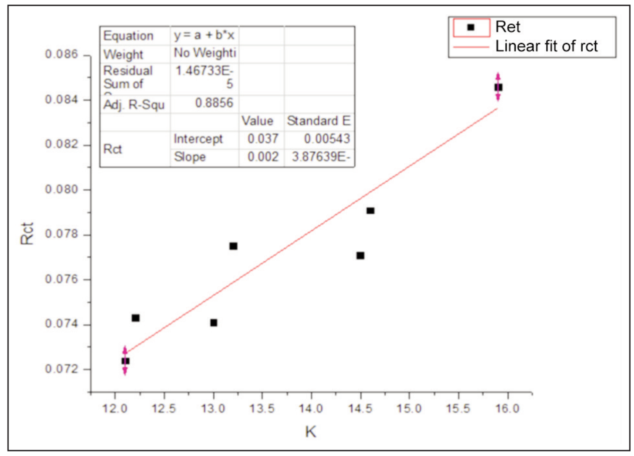
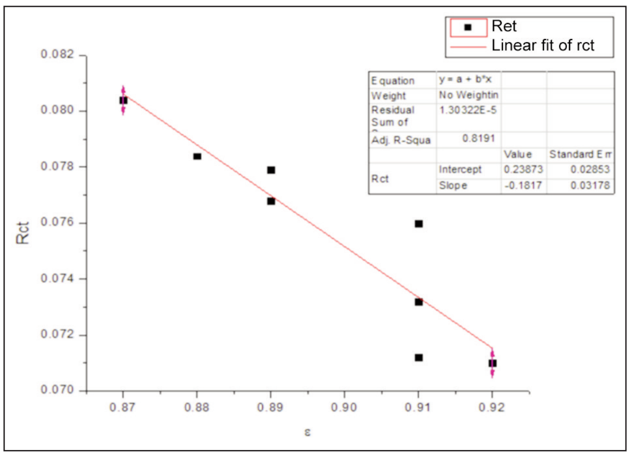


Fig. 6. Relationship between Rct and K in 100% Co bleached and dyed knitwear, $R^2 = 0.86627$

Fig. 7. Relationship between Rct and K in 96% Co/4% Ly bleached and dyed knitwear, $R^2 = 0.8856$



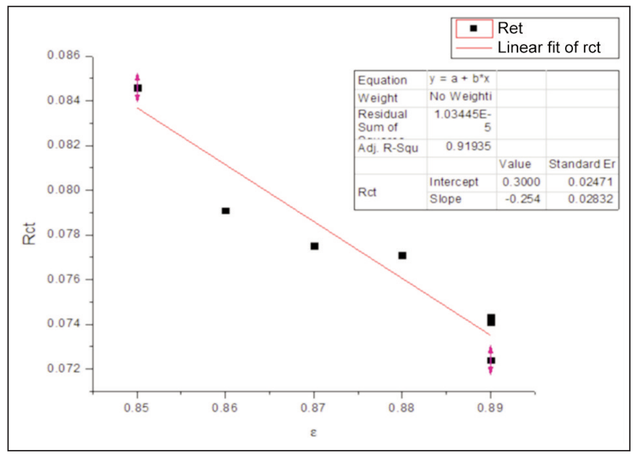


Fig. 8. Relationship between Rct and K in 100% CO bleached and dyed knitwear, $R^2 = 0.8191$

Fig. 9. Relationship between Rct and K in 96% CO/4% LY bleached and dyed knitwear, $R^2 = 0.9193$

Table 3

VALUES OF COEFFICIENTS USED FOR CALCULATING RCT BLEACHED AND COLORED RIBBED 1×1 KNITWEAR

Sample	Finishing	Coefficient c_1	Coefficient c_2	Coefficient c_3	Coefficient c_4
BP1-BP4	bleaching	–0.000252	0.018443	0.016669	–0.35311
CP1-CP4	colouring	0.000089	0.000366	–0.00096	0.07245
BL1-BL4	bleaching	0.000038	0.01346	0.02263	–0.3662
CL1-CL4	colouring	0.00174	0.00225	0.1167	–1.5693

lycra woven from cotton yarn of fineness 20, 17, 14 and 12 tex.

The mathematical model for calculating the value of Rct has the following form:

$$Rct = c_1 \cdot d_{pl} + c_2 \cdot K + c_3 \cdot \delta_p + c_4 \cdot \varepsilon \qquad (3)$$

where c_1, c_2, c_3, c_4 are coefficients, d_{pl} – knitwear thickness, K – coverage factor, δ_p – surface coefficient, ε – knitwear porosity.

CONCLUSIONS

According to the conducted research of the impact of yarn thickness and raw material composition, i.e. the influence of lycra on thermal resistance in ribbed knitwear, following can be concluded:

- Knitwear that, beside cotton yarn, have lycra in their composition, are more compact and therefore heat resistance increases with these samples.
- With a change in the fineness of the cotton yarn i.e. with a decrease in the thickness of cotton yarn and thermal resistance decreases by 13% in cotton yarn knitwear and up to 16% in knitwear with lycra in its composition. From the obtained results we can conclude that in knitwear made from 100% cotton yarn, the fineness of 12 tex shows the lowest

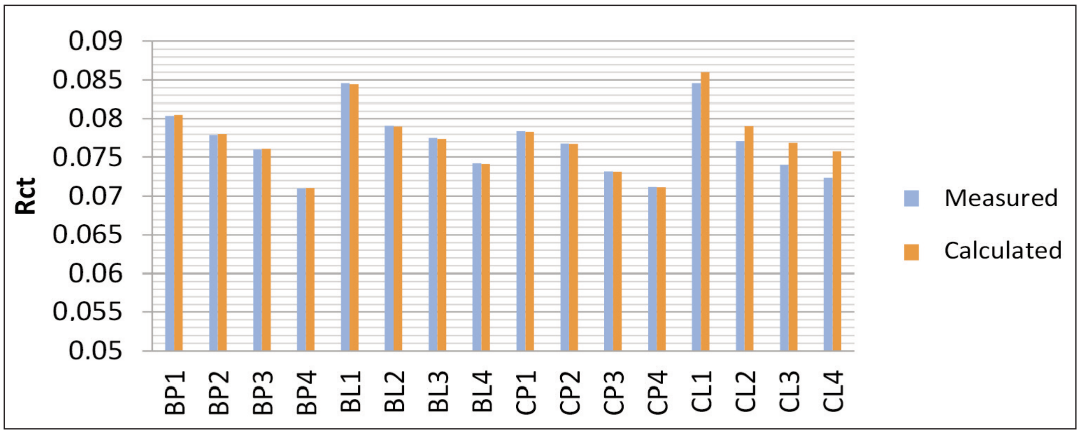


Fig. 10. Graphical representation of the deviations between calculated and measured values of Rct

thermal resistance. While the highest thermal resistance is observed in knitwear that has lycra and cotton yarns of fineness 20 tex in their composition. Also, this paper presents and verifies the correlation between the measured values of thermal resistance (*Rct*) and the knitwear thickness (*dpl*), the covering factor (*K*), the porosity of the twists (ε) and the surface coefficient (δ_p). Based on these results, a mathematical model for calculating thermal resistance is proposed. Comparing the results obtained with the proposed equation and the measured results, we can see that the deviations are minimal. The highest deviation for sample C4 is 0.05%, while the largest deviation for sample CL4 is 4.6%.

Based on the results obtained, we can conclude that knitwear intended for wearing to the body are made of 100% cotton yarn have lower values of heat resistance and are recommended for wearing in warmer weather, while knitwear with lycra is recommended for wearing to the body in colder weather due to higher thermal insulation results.

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