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Thermal resistance of multi-layer fabrics considering layer order

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The impact of number and order of layers in various sets of multi-layer fabrics has been investigated. Four groups of polyester fabrics with different thicknesses and thermal resistance have been analysed. Moreover, the thermal resistance of various two-, three- and four-layer combinations are evaluated. Results reveal that by increasing the number of layers in a multi-layer set, besides the effect of each layer's thermal resistance, the formation of air layers between constituent fabric layers, results in a considerable growth in the thermal resistance. Furthermore, it is demonstrated that the order of layers in a specified combination of fabrics, influences the thermal resistance of the multi-layer samples. Statistical analysis of results confirms the significant influence of the number and order of layers on the thermal resistance characteristic of multi-layer fabrics.

Keywords: Air layer thickness, Order of layers, Multi-layer fabric, Polyester, Thermal resistance

1 Introduction

In cold weather conditions, human body loses its heat due to the heat transfer to environment and this can be risky for the human well-being. Wearing clothes is the most common way to protect body against heat loss. However, thermal resistance of clothing determines its ability to avoid the body heat loss. In this regard, Seames *et al.*[1] quantified the thermal conductivities and thermal resistances of a group of fabrics extracted from commercial clothes which were designed for the extremely cold climate. Tang *et al.*[2] presented a multi-scale modeling of human thermal regulation and the assessment of human thermal comfort in terms of clothing properties. In this research, the required thermal resistance for comfortable clothing in the human resting condition under different environmental temperatures from -5ºC to 20ºC was also estimated. Mathur *et al.*[3] focused on the requirements of protective clothing for extreme cold weather circumstance and suitable clothing system for such condition. Tugrul Ogulata[4] investigated the thermal comfort of the body with regards to the various mechanisms of body's heat transmission, body movement and weather condition and presented main mechanisms of body heat loss based on the mentioned parameters. Matusiak[5] established a model based on the structural parameters of plain-woven fabric on the purpose of predicting its thermal resistance. Annaheim *et al.*[6] compared dry thermal insulation of fabric that was measured by a developed sweating Torso device and sweating guarded hotplate method. Obtained results of both methods were consistent. Shen *et al.*[7] analyzed the heat transfer through a fabric by finite element method, in which heat transmission in vertical and horizontal direction of yarns were considered.

Although thick textiles due to the high amount of entrapped air usually have higher thermal insulation and can be a proper selection for cold climates, this batches of clothing are bulky and heavy so they can provide a discomfort situation. Therefore, the application of multi-layer clothing has been considered in some researches to improve the thermal resistance of clothing. In this regard, not only the thermal insulation of each constituent layer, but also the air layer that is formed between fabric layers can enhance the thermal insulation of the multi-layer clothing. In a study, Ann Morris[8] investigated the thermal insulation performance of single layer and multi-layer fabrics composed of various fibre blends. Gnanauthayan *et al.* [9] during the evaluation of the heat insulation characteristics of high bulk nonwovens listed the fibre denier, fibre cross-section and bulk density, porosity and thickness of nonwovens as the effective parameters on the thermal resistance of nonwovens' layer. Since heat transfer in the clothing's microclimate has a critical impact on the clothing's insulation, Nadzeikiene *et al.*[10] probed the

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influence of air layer thickness that is formed between the clothing and the skin on the clothing's insulation characteristics. Although the thermal comfort of the clothing depends on the surrounding temperature, Sirvydas *et al.*[11] presented that determining proper thickness for clothing's system would lead to a steady state heat transfer phenomenon. Das *et al.*[12] investigated the impact of forming air layer between two consecutive layers in multi-layer clothing both theoretically and experimentally. Li *et al.*[13] measured the thickness of the air layer that is formed between clothing and skin by a 3D-body scanner and developed a regression model in order to predict the thermal insulation of clothing system. Matusiak *et al*.[14] inspected the relation of the thermal insulation of multi-layer clothing system with the thermal resistance of its constituent layers. Dabrowska[15] studied the effect of clothing size and design elements on the thermal insulation of protective clothing system in cold weather condition. Chen *et al.*[16] investigated the effect of air-gap thickness on the thermal insulation of the clothing and announced that the thermal insulation reached a maximum at a certain air-gap thickness concerning the fabric properties and the clothing fit.

The number of layers in the multi-layer clothing, due to the thermal insulation of each layer and formation of air layer between successive layers, can raise the thermal insulation of multi-layer clothing. In this respect, Sun *et al.*[17] conducted a study on heat transfer through a textile assembly composed of fabric and air layers by the utilization of finite element method, in order to evaluate the alteration of heat flux with regards to the time and the transit temperature distribution at the cross-section of the fabric assembly. It was concluded that the size of the air gaps significantly influences the heat transfer phenomenon. Gupta *et al.*[18] concentrated on the influence of layering fabrics with and without air gaps between them as a simulation of a multi-layered clothing assembly and proved the remarkable effect of inner and outer layer pairing on the thermal insulation of clothing. Matusiak *et al.* [19] in accordance to the study of the thermal insulation properties of clothing made of the fabrics, revealed that the clothing design, fitting to the user's body, and the number of layers have a dominant role in the occurrence of the heat exchange between the human body and its environments. Dabrowska[20] analyzed different aspects of fit and clothing construction on the clothing thermal insulation against cold. In this paper, the use of overlock seams for creation of air gap between the clothing layers was recommended for provision of additional thermal insulation. Gnanauthayan *et al.*[21] studied the effect of compression on thermal resistance of multilayer nonwoven structures. In this research, it was revealed that in a multi-layer nonwoven, fine solid fibres had poor performance in case of compression and recovery, which led to weaker thermal resistance. It was also concluded that three-layered nonwoven structure, provided better thermal resistance than their single component equivalents. Since body perspiration during high level of physical activity is inevitable, Garg *et al.*[22] assessed the influence of body perspiration on the thermal insulation of three layer garments. Their outcomes reveal that both wetting and the type of aqueous solution can affect the thermal insulation. In this regard, the thermal insulation of samples dampened with simulated sweat is higher than sample dampened with distilled water.

By reviewing previous researches, it can be perceived that the use of multi-layer clothing instead of thick and heavy single-layer clothing can provide the desired thermal insulation property. Besides, it may offer better wearing comfort. The number of layers, the thermal insulation of the constituent layers and air layer that are formed between them can change the obtained thermal resistance. However, it seems that the arrangement of the layers may influence the insulation of the multi-layer clothing as well.

In view of above, the present study was aimed at investigating the thermal insulation of various compositions of one-, two-, three- and four-layer clothing, both theoretically and experimentally.

2 Materials and Methods

2.1 Materials

In case of multi-layer clothing, since the utilization of a variety of layers for prevention of the body heat loss is of great importance, in this study it was tried to use different kinds of fabrics as various layers of multi-layer sample and analyse the effect of the number and also the order of layers on the thermal resistance of the multi-layered sets. In this regard, four diverse samples were used (Table 1).

As it can be observed, selected fabrics differ in terms of structure, weight, density and thickness. It should be noticed that the aim of this study is to probe the influence of the number of layers and their order on the thermal resistance of multi-layer sample. In other words, the purpose of this research is to evaluate the effect of thermal resistance of each layer on the variation of thermal resistance of multi-layer samples with different layer order.

2.2 Sample Preparation

As it was mentioned before, the aim of this investigation is to analyze the influence of the number and order of layers in multi-layered fabric assemblies on the thermal insulation, the experiments were performed for different combinations of layers.

At the first stage of tests, the thickness and thermal resistance of each single layer (Table 1) was measured. Then all possible two-layer, three-layer and four-layer arrangements were composed. The combinations with different number and order of layers are illustrated in Table 2.

Each combination code reveals the top and bottom layers. Besides, for the direct focus on the impact of layering on the thermal resistance of multi-layer assemblies, collections of similar layers were also evaluated.

2.3 Test Procedure

2.3.1 Thickness Measurement

In order to evaluate the thickness of the single layer fabrics, the Shirley thickness tester was utilized and the test was carried out according to the standard test method of ASTM D1777 and under the normal pressure of 20 g/cm^2. Finally, the mean of 10 repetitions was reported as the thickness of each fabric. It should be noted that for the thickness of multi-layered samples (more than one layer), the summation of the thickness of all consisting single-layers was reported.

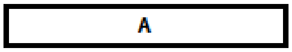
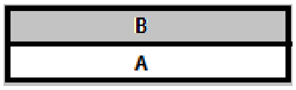
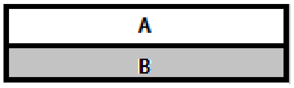
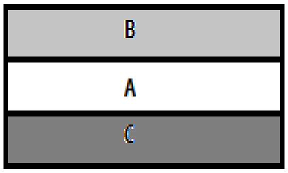
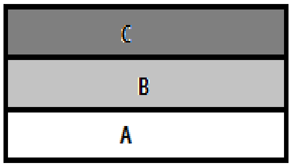
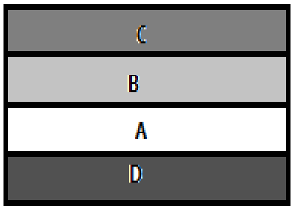
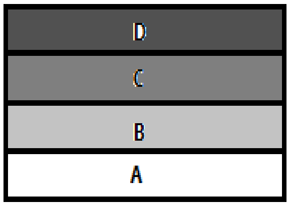
2.3.2 Thermal Resistance Evaluation

The thermal resistance (thermal insulation characteristics) of each single layer and also the

Table 1 — Fabric characteristics

Sample code	Fabric	Fibre composition	Areal weight, g/m^2	Density	Thickness, mm
A	Woven fabric (plain)	Polyester	355	46 warps/cm 25 wefts/cm	1.45
B	Double jersey knitted fabric	Polyester	385	2 coarses/cm 4 wales/cm	2.24
C	Fleecy knitted fabric	Polyester	276	17 coarses/cm 12 wales/cm	1.22
D	Woven fabric (weft-backed twill 2/1)	Polyester	350	29 warps/cm 33 wefts/cm	0.97

Table 2 — Various grouping of layers

Number of layers	Arrangement of layers	
Single-layer		
Two-layer	 AB	 BA
Three-layer	 CAB	 ABC
Four-layer	 DABC	 ABCD

combination of various layers (multi-layer fabric assemblies) was assessed based on the BS 4745 standard test method, using the Tog-meter testing device. Two experimental approaches were proposed in this standard test method, which were the single plate method and two-plate schemes (employed in the present study). The representation of the Tog-meter apparatus while using the two-plate method is shown in Fig. 1.

From this experiment, the value of thermal resistance (R_f) was calculated using the following equation.

$$R_f = R_{stand} \times \left(\frac{T_2 - T_3}{T_1 - T_2}\right) - R_{air} \qquad \ldots (1)$$

where R_f is the thermal resistance of the tested sample (single or multi-layer); R_{stand}, the thermal resistance of standard material (in this study wood with R = 0.0684 (m^{2o}C/W); T_1, the heater temperature; T_2, the temperature between standard and tested sample; T_3, The temperature above tested sample; and R_{air}, the thermal resistance of air.

The value of R_{air} was estimated before the beginning of the sample testing. R_{air} is the thermal resistance caused by the presence of air between the standard and the top plate, so the test for evaluation of R_{air} was performed without placing any samples between the stated plates. The air thermal resistance (R_{air})was calculated using the following equation:

$$R_{air} = R_{stand} \times \left(\frac{T'_2 - T'_3}{T'_1 - T'_2}\right) \qquad \ldots (2)$$

where T' are the temperatures only in the presence of air.

Since Tog-meter plates are circles with the diameter of 33 cm, in order to measure thermal resistance of samples, test specimens were cut in circles with the diameter of 33 cm. According to the configuration of the Tog-meter testing device (Fig. 1), the heater was placed below; hence, the bottom layers always were near to the heater. It should be noted for each condition, the experiments are repeated five times and that the mean of the results obtained from 5 repetitions of the test was recorded as the thermal resistance of each fabric and multi-layer combination.

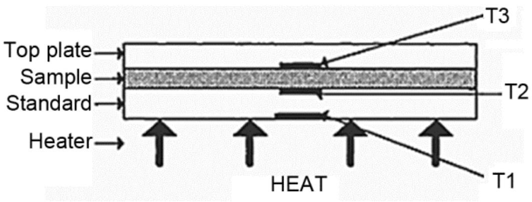


Fig. 1 — Two-plated tog-meter instrument

By determining the thermal resistance of the single and multi-layer samples, the thermal conductivity (K) was calculated using the following equation:

$$K = \frac{d}{R_f} \times 10^{-3} \qquad \ldots (3)$$

where K is the thermal conductivity (W/mºC); R_f, thethermal insulation (m^{2o}C/W); and d, the total single or multi-layer assembly's thickness (mm).

3 Results and Discussion

3.1 Thermal Properties of Single-layer Fabrics

Due to the importance of the thermal behaviour of each single layer sample, in determination of the properties of different multi-layer compositions made from them, the thermal properties of all individual fabrics are investigated.

The thermal resistance (the thermal insulation properties) of each single layer fabric dominantly affects the thermal insulation of the multi-layer fabric, as calculated from Eq. (1). Besides, in order to evaluate the way, the fabric thickness impacts the thermal resistance of fabrics. The thickness of the single layer samples was also measured under the pressure of 20 g/cm^2. According to Eq. (3), the thermal conductivity of the mentioned fabrics has been calculated with regards to the effect of fabric thickness. Thermal resistance of tested fabrics including A, B, C and D are 0.2, 0.4, 0.12 and 0.06 m^{2o}C /W; however, their thermal conductivities are 0.00725, 0.0056, 0.0102 and 0.0162 W/m ºC, respectively.

It is apparent that the highest thermal resistance among the investigated fabrics belong to sample B, which has higher areal weight and thickness as compared to other fabrics. Sample B is a double jersey knitted fabric with low stitch density and composed of coarse yarns, which facilitates the presence and trapping of considerable amount of air as a thermal insulator in the fabric structure; this results in better thermal resistance of this fabric.

After fabric B, the next higher thermal insulation ability is obtained for fabric A, which is a plain woven fabric with a high areal weight and thickness and fluffy surface due to the brushing treatment. The mentioned properties of fabric A lead to its reasonable thermal resistance. Fabric C which is a fleecy knitted fabric is lighter than fabric A and has lower thickness as compared to A, which leads to its poorer thermal insulation. Finally, fabric D which is a woven fabric and has the lowest thickness of all fabrics has the lowest thermal resistance. In this regard, fabrics B and D show the lowest and highest thermal conductivity respectively.

According to the results, it seems that regardless of fabric structure, the fabric thickness is one of the dominant factors affecting the fabric's thermal insulation. In fact, by increasing the fabric thickness, due to the rise in the amount of entrapped air in the fabric structure, the thermal insulation of the fabric improves.

Statistical analysis of results at the confidence range of 95% reveals that the four investigated fabrics have significant difference with regards to their thermal insulation properties and also thickness.

3.2 Thermal Characteristics of Two-layer Sets

In this part, all double-layer combinations of fabrics A, B, C and D are investigated in order to analyse the effect of each layer type, orientation and ordering of layers. Different mixtures of fabrics, each having two orders, results in twelve testing sets (Table 3). As it is mentioned before, the thermal resistance of two-layer sets is evaluated (Table 3). Moreover, the thermal conductivity of each set is calculated by consideration of the thickness of each double-layer combination.

According to the results, it is observed that the components of each two-layer set have an important effect on their thermal resistance. Fabric B, which has the highest thickness and thermal resistance among all fabrics, when exists in a pair, shows the rising trend of thermal insulation, and the combinations of AB, BA, BC and CB have higher thermal resistance. Moreover, the two-layer sets of fabrics A and B together (both having better thermal resistance compared to other fabrics) show the highest thermal resistance. In the sets containing B and D fabrics, due to the low thermal resistance of fabric D, it seems that fabric B has the dominant role in determining thermal resistance of the two-layer set.

Another interesting point (Table 3) is that in case of similar combination of fabrics, by the alteration of the layer's ordering, the thermal resistance of the set has changed. It seems that this outcome is related to the thermal insulation of individual layers. In other words, placing the layer with higher thermal resistance near to the heater improves the performance of the combination to reduce heat loss rate.

In order to statistically analyze the effect of fabric type and ordering in two-layer sets, ANOVA tests at significance level of $\alpha = 0.05$ has been carried out. ANOVA results show that the effect of fabric type and layer ordering in a set is significant on the thermal resistance. In addition, the thermal conductivity of various combination having two orders of layers has been calculated (Table 3) and it is observed that by increasing the thickness of sets, the thermal conductivity is decreased.

3.3 Thermal Features of Three-layer Sets

In this section, the thermal characteristics of three-layer combinations are reported and analysed. By combining the four single fabrics, four three-layer combinations including ABC, ABD, ACD and BCD have been investigated. The thickness of these four fabric combinations are 4.90, 4.66, 3.64 and 4.43 mm respectively. As it is perceived, the highest and lowest thickness belongs to ABC and ACD combinations correspondingly.

Since the ordering of fabrics in each combination has to be considered as well, on the whole 24 sets (Table 4) are evaluated for thermal resistance. Based on the outcomes of thermal resistance and also the thickness of groups, the thermal conductivity of three-layer samples is also calculated (Table 4). It is detected that by increasing the number of layer and consequently the thermal resistance of multi-layer sets, the thermal conductivity of fabric combinations is decreased.

The influence of the layer type on the thermal resistance of three-layer sets are analysed (Fig. 2), in a

Table 3 — Thermal characteristics and thickness of two-layer sets

Property	AB Fabric	BA Fabric	AC Fabric	CA Fabric	AD Fabric	DA Fabric	BC Fabric	CB Fabric	BD Fabric	DB Fabric	CD Fabric	DC Fabric
Thickness, mm	3.69		2.67		2.42		3.46		3.20		2.19	
Thermal resistance m^{2} ºC /W	0.54	0.68	0.34	0.21	0.33	0.22	0.53	0.41	0.45	0.37	0.23	0.15
Thermal conductivity W/m ºC	0.0068	0.0054	0.0079	0.0127	0.0073	0.011	0.0065	0.0084	0.0071	0.0086	0.0095	0.0146

Table 4 — Thermal characteristics of three-layer sets

Fabric	Thermal resistance m^{2}°C /W	Thermal conductivity W/m °C
ABC	2.21	0.0022
ACB	2.34	0.0021
BAC	2.38	0.0021
BCA	2.67	0.0018
CAB	2.60	0.0019
CBA	2.53	0.0019
ACD	0.62	0.0056
ADC	0.58	0.0063
CAD	0.69	0.0053
CDA	0.78	0.0047
DAC	0.75	0.0049
DCA	0.71	0.0051
ABD	1.38	0.0034
ADB	1.67	0.0028
BAD	1.18	0.0039
BDA	1.49	0.0031
DAB	1.22	0.0038
DBA	1.27	0.0037
BCD	0.92	0.0048
BDC	0.94	0.0047
CBD	0.98	0.0045
CDB	1.05	0.0042
DBC	1.11	0.0040
DCB	1.15	0.0039

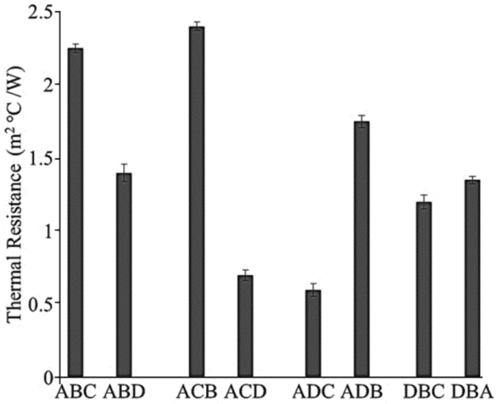


Fig. 2 — Effect of layer type on thermal resistance of three-layer sets (CI 95%)

way that two layers are remained constant and only the third layer is changed, and the thermal resistance of three-layer compositions are compared paired-wise.

Figure 2 shows that in comparison of four three-layer sets ABC, ABD, ACB and ACD, it is evident that the presence of fabric D diminishes the thermal resistance. As it is mentioned previously, fabric D is a high density fabric having lowest thickness. In addition, in comparison with other fabrics, it has the lowest thermal resistance. Consequently, when this fabric is added to a fabric assembly, its impact on the thermal resistance of fabric assembly is not considerable.

In case of ADC, ADB and ACB, ACD samples, addition of fabric B leads to better thermal resistance as compared to addition of fabrics C and D. The thicken structure of fabric B and its ability to entrap air in its structure is the reason for the obtained results.

Finally, for DBC and DBA samples, it is observed that the presence of fabric A enhances the thermal resistance better than fabric C. As it is stated before, thickness and thermal resistance of fabric A are higher than those of fabric C. In this regard, addition of this layer to the fabric assembly increases the thermal resistance of multi-layer fabrics.

Besides the effect of layer type, by changing the order and positioning of similar layer types in a combination, it is observed that the thermal resistance might vary (Table 4). It can be said that for combination of fabrics A, B & C, the thermal resistance changes from 2.21m^{2}°C /W to 2.67m^{2}°C /W, for combination of fabrics A, C & D, it is changed from 0.58 to 0.78, for fabrics A, B and D combination variation of thermal resistance was from 1.18m^{2} °C / W to 1.67m^{2} °C /Wand finally for the mixture of fabrics B, C & D it changes from 0.92m^{2} °C / W to 1.15m^{2} °C /W. The variation of thermal insulation of multi-layer samples with the same layer type and different order of layers can be due to the thermal insulation of individual layers and their weight. Although placing of layer with higher thermal insulation adjacent to the heater can diminishes the heat loss rate of the combination, the weight of the above layers due to the exerting pressure on the below layers can decrease their thickness and, in turn,entraps air layer thickness that leads to the reduction in thermal insulation. In addition, as it is mentioned previously, in the multi-layer samples, the constituent layers are not joined to each other; hence, the heat loss from the layer edges is possible.

Statistical analysis of results also made clear that at the confidence range of 95% the effect of fabric type and layer ordering on the thermal resistance results is significant.

3.4 Thermal Properties of Four-layer Combinations

For the last series of tests, the thickness and thermal characteristics of four-layer combinations are estimated and analysed. The point about this category of tests is that all the testing sets has identical layers consisting of fabrics A, B, C and D and only the order of layers is changed. The thickness of all four-layer samples is 5.88 mm. With regards to the variation of layer positioning, 24 sets of experiment have been investigated and their thermal resistance andthermal conductivity are calculated (Table 5).

According to the results, itIs noticed that despite the similarity of the components of four-layer samples, the thermal resistance of them differs from 7.75m^2 ºC /W to 12.2m^2 ºC /W, which indicates that the order of the placement of various fabrics has affected the combination's thermal resistance.

On an average, in fabrics combination wherein fabric B is positioned in the lowest level (near the tog-meter heater), the thermal resistance is improved. Since in this experiment the four various layers are only laid on each other without any joining process, it seems that by the positioning of layers in a four-layer sample, although the thermal resistance has increased compared to single fabrics or compositions containing fewer layers, but there is possibility of heat loss from layer edges. Therefore, the placement of a layer with reasonable thermal resistance near the heater assists the preservation of heater's produced heat.

Table 5 — Thermal properties of four-layer sets

Fabric	Thermal resistance m^{2}ºC /W	Thermal conductivity W/m ºC
ABCD	11.07	0.0005
ABDC	10.12	0.0006
ACBD	10.42	0.0006
ACDB	11.15	0.0005
ADBC	10.30	0.0006
ADCB	10.31	0.0005
BACD	12.20	0.0005
BADC	11.70	0.0005
BCAD	11.62	0.0005
BCDA	11.60	0.0005
BDAC	12.08	0.0005
BDCA	11.78	0.0005
CABD	9.30	0.0006
CADB	10.34	0.0006
CBAD	10.05	0.0006
CBDA	10.21	0.0006
CDAB	9.60	0.0006
CDBA	9.90	0.0006
DABC	8.18	0.0007
DACB	7.89	0.0007
DBAC	8.95	0.0007
DBCA	8.70	0.0007
DCAB	7.75	0.0008
DCBA	7.96	0.0007

On the whole, statistical analysis of results by utilization of ANOVA test, confirms the effectiveness of layer ordering in a four-layer set, on its thermal resistance in the confidence level of 95%.

In evaluation of the thermal conductivity (W/m ºC) of multi-layer compositions, it is clear that by increasing the number of layers, the total thermal conductivities of multi-layer structures, has decreased significantly.

3.5 Calculation of Thermal Insulation of Multi-layer Samples based on the Fourier's Law

According to the Fourier's law, conduction heat transfer through a body as a result of a temperature difference can be described by following equation:

$$Q = -KA\frac{\Delta \mathrm{T}}{\mathrm{x}} \qquad \ldots (4)$$

where Q is the heat transfer rate (W); K the thermal conductivity of the clothing (W/mºC); A, the areal surface of body (m^2); ΔT, the temperature difference between body surface and atmosphere (°C); and x, the clothing's thickness (m).

In multi-layer clothing that consists of more than one layer, which can be different in terms of thickness and thermal conductivity (Fig. 3), in the steady state conduction condition, the heat flow through all layers are similar as it is displayed in following equation:

$$Q = -K_A A\frac{T_2 - T_1}{x_A} = -K_B A\frac{T_3 - T_2}{x_B} = -K_C A\frac{T_4 - T_3}{x_C} \qquad \ldots (5)$$

By solving these equations concurrently, the heat transfer through multi-layer clothing can be obtained by following equation:

$$Q = \frac{T_1 - T_4}{\frac{x_A}{K_A \times A} + \frac{x_B}{K_B \times A} + \frac{x_C}{K_C \times A}} \qquad \ldots (6)$$

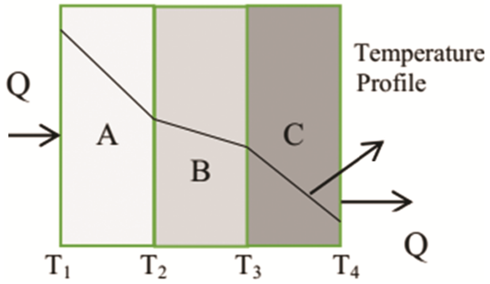


Fig. 3 — Heat transfer throught multi-layer clothing

In this regard, overall thermal resistance of multi-layer clothing can be expressed by the following equation:

$$R = \sum_{1}^{n} \frac{x_i}{K_i \times A} \qquad \ldots (7)$$

According to Eq. (7), the thermal resistance of various multi-layer clothing are calculated and the achieved outcomes are illustrated in Table 6.

As it is shown in Table 6, in calculated thermal resistance of sets, the influence of layer orders is not considered and the overall thermal resistance of each multi-layer specimen depends on the thermal resistance of constituent layers. As an example, theoretical and experimental of thermal resistance of three-layer clothing are presented in Fig. 4.

As it is shown in Fig. 4, there is a large difference between calculated and measured thermal resistance of three-layer samples. In fact, during the calculation of thermal resistance, the interaction between layers is neglected and just the impact of thermal resistance of each layer is considered. However, when fabrics are placed over each other, due to the roughness of fabric surface, small distances are formed between each adjacent layer that leads to development of air layer. Since air is an effective thermal insulator, it has a critical role in the enhancement of the multi-layer clothing's insulation. It should be noted that during the calculation of thermal resistance of multi-layer clothing, the influence of this air layer is omitted, while one of the main reasons of application of multi-layer clothing for extremely cold weather condition is the progress of this air layer. As it is mentioned previously, thermal resistance of multi-layer samples, composed of similar layers,is examined as well. The results of the measured and calculated thermal resistance of three-layer specimens are illustrated in Fig. 5.

As it is shown in Fig. 5, the same results are observed for three-layer samples containing similar layers, and this confirms the influence of presence of air layer as a good insulator layer between fabrics.

3.6 Influence of Number of Layers on Thermal Insulation

The effect of number of layers on the thermal resistance of multi-layer clothing is presented in Fig. 6. According to Fig. 6, the increase in number of

Table 6 — Calculated thermal resistances of multi-layer sets

Fabric	Thermal resistance, m^{2o}C /W
AB	0.615
AC	0.306
AD	0.266
BC	0.521
BD	0.481
CD	0.172
ABC	0.78
ABD	0.66
ACD	0.38
BCD	0.58
ABCD	0.78

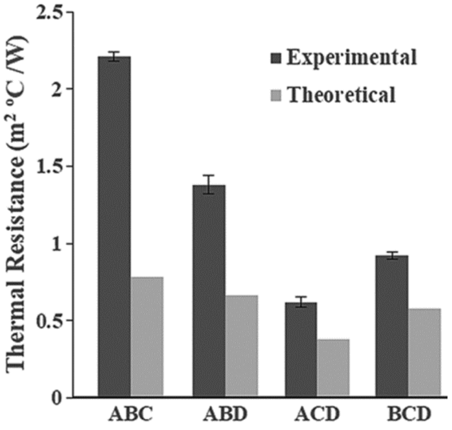


Fig. 4 — Comparison of theoretical and experimental thermal resistance in three-layer sets (CI 95%)

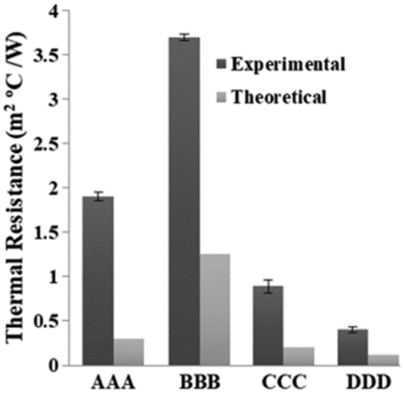


Fig. 5 — Comparison of theoretical and experimental thermal resistance in three-layer sets consisted of similar layers (CI 95%)

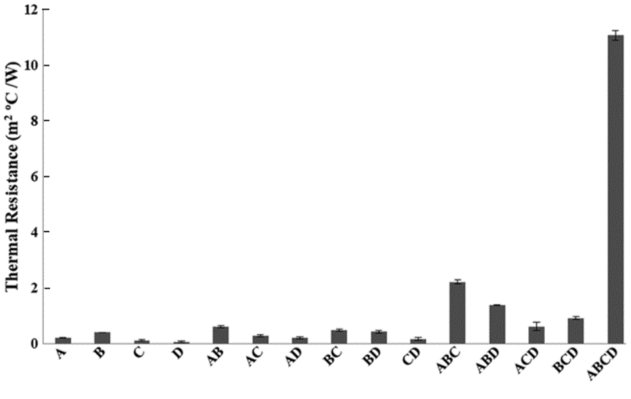


Fig. 6 — Influence of number of layers on thermal insulation of multi-layer clothing (CI 95%)

layers leads to the raise of thermal insulation. The increment of the thermal insulation of samples is due to the increase of the number of layers and the air layer that is formed between layers. It is observed that by utilizing three or more layers in the multi-layer clothing, a considerable increase in the thermal resistance is obtained. This outcome indicates that the application of multi-layer clothing is an effective method to improve thermal insulation. Therefore, this technique is used in preparation of protective clothing for cold and extremely cold weather conditions.

3.7 Effect of Layer's Orientation on Thermal Insulation

In order to investigate the influence of layers' order on the variation in thermal resistance of multi-layer clothing, the method used by Yavari Rameshe *et al.*[23] has been used. According to this method, the results of thermal resistance of two-layer samples and their order are considered as a square matrix. Each entry of matrix is related to a two-layer specimen. In this regard, if the obtained matrix with respect to its main diagonal is a symmetric one, then the order of layers in various samples does not affect the thermal insulation. The entries of the thermal resistance can be described as $R = (R_{ij})$ and for a symmetric matrix, the relationship is given below:

$$R = \begin{bmatrix} R_{AA} & R_{AB} & R_{AC} & R_{AD} \\ R_{BA} & R_{BB} & R_{BC} & R_{BD} \\ R_{CA} & R_{CB} & R_{CC} & R_{CD} \\ R_{DA} & R_{DB} & R_{DC} & R_{DD} \end{bmatrix} \quad \ldots (8)$$

$$R_{ij} = R_{ji}$$

According to the mathematical basis, a symmetric matrix is equivalent to its transpose. On the aim of assessment of thermal resistance's symmetry, this characteristic is considered. In order to acquire off-diagonal components of the upper triangular matrix, the diagonal matrix is detracted of the upper triangular matrix of R, as follow:

$$R_{off-diagonal} = R_{UpperTriangular} - R_{diagonal} \quad \ldots (9)$$

where $R_{diagonal}$ is the diagonal matrix of thermal resistance that consisted of the main diagonal of the desired matrix; and $R_{UpperTriangular}$, the upper triangular matrix of R .

It is clear from the following equation that the transpose of $R_{off-diagonal}$ presents the transpose of the upper triangular matrix of R , in which the entries of the main diagonal are omitted:

$$TR = R^{T}_{off-diagonal} \quad \ldots (10)$$

According to following equation, by summation of the TR and $R_{UpperTriangular}$, the main thermal resistance matrix will be obtained, if the matrix is a symmetric one:

$$R' = TR + R_{UpperTriagular} \quad ... (11)$$

The difference between main thermal resistance matrix and the computed one is calculated based on the following equation:

$$Error = R - R' \quad \ldots (12)$$

In a symmetric matrix the difference matrix will be zero. However, the main matrix is achieved according to the trial results, and errors are inevitable. Thus, norm of the error matrix and original matrix are calculated using the following equation:

$$\begin{aligned} N_{Error} &= \|Error\| \\ N_R &= \|R\| \end{aligned} \quad \ldots (13)$$

To determine the difference ratio of the error and thermal resistance matrix, norm of the former is divided by norm of the latter as it is shown below:

$$ErrorValue = N_{Error}/N_R \quad \ldots (14)$$

Error value is a factor to inspect the deviation of the thermal insulation matix and its transpose. In this regard, if this value is close to zero, then the thermal resistance matrix is almost symmetric. Based on the performed calculation this error value is obtained as 0.1489 and it seems that thermal resistance matrix is not symmetric. This states that the order of layers in a multi-layer clothing affects its thermal resistance.

4 Conclusion

Application of multi-layer clothing in order to protect human body against heat loss in extremely cold weather condition has been considered instead of utilizing of heavy and thick clothing. Due to the formation of air layer between each two adjacent layers and the high insulation property of the air, these clothings have high thermal resistance. However, not only the number of layers and their thermal insulation, the arrangement of layers may affect the thermal resistance of multi-layer clothing, as well. In this respect, four fabrics with different thicknesses and thermal insulations are used to prepare various multi-layer samples which include two, three and four-layer assemblies. Then, the thermal resistance of all individual layers and multi-layer samples are inspected by tog-meter method. Furthermore, in each multi-layer fabric, the influence of the variation in layers' order on their thermal insulation are also investigated. In addition, the thermal insulation of multi-layer sampleis calculated with the aid of Fourier's law. According to the outcomes, increasing the number of layers due to the each layer's thermal insulation and also the formation of air layer and its good thermal resistance,improve the thermal resistance of multi-layer specimen. In various multi-layer fabric, the calculated thermal insulation is lower than the experimental value. Because during the calculation of thermal insulation, the impact of air layer thickness is neglected; however, it has a great affect on the thermal resistance. Moreover, the effect of the order of layers in a multi-layer composition of the textiles, on its thermal resistance is found significant at 95% confidence level. It means that in multi-layer samples with the same number of layer and constituent elements, the order of placing the layer can also change the thermal insulation. It appears that the insertion of layer with higher thermal resistance helps in decreasing the heat transfer rate to the surroundings. However, the weight of beyond layers can negatively affects the thermal insulation of the multi-layer constructions, by applying pressure on the beneath layers and reducing the entrapped air capacity. Furthermore, since the layers are not jointed to each other, the possible heat transfer of layer edges is the another point that can affect the thermal insulation of samples.

Consequently, the thermal insulation of each combination is a complex issue that depends on the outcomes of all mentioned parameters. Furthermore, mathematical analysis based on the property of symmetric matrixes confirm the obtained results.

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