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## Comparative Analysis of Protective Garments System with Fleece and Spacer Based Removable Inserts

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### Abstract

The measurement results for the thermal insulation of the outer shell, removable thermal inserts, and protective garments system (PGS), as well as a comparative analysis of the thermal insulation, are presented. Both protective garments systems are made from the same materials. One removable thermal insert is made of fleece, while the other is made of spacer material. Tests of the thermal properties of the protective garments system were conducted using a thermal manikin. These studies have shown that the primary contributors to thermal insulation are the removable thermal inserts, while the outer shell, made of laminate, serves a protective function against wind and moisture. From the measured thermal insulation values and established results, it is evident that the outer shells of both protective garments systems have values slightly greater than 1 Clo, while the removable thermal inserts in the protective garments system have significantly higher thermal insulation values of 1.45 and 1.78 Clo. Thus, the total thermal insulation increases to about 2.3 Clo, indicating that removable thermal inserts can more than double the thermal insulation of the protective garments system.

**Keywords:** protective garments system, thermal insulation, thermal mannequin

### 1. Introduction

Garment plays a key role in maintaining thermal balance and significantly affects thermal comfort. Gagge et al. published a paper in 1941 proposing the unit of measurement Clo ( $1 \text{ Clo} = 0.155 \text{ m}^2\text{K W}^{-1}$ ) for determining the thermal insulation of garment [1, 2], which was later used as an important parameter in thermal comfort models [3, 4]. Clo is defined as a unit for measuring the thermal insulation value of garment, where 1 Clo refers to a person who feels thermally comfortable when sitting in a ventilated room with an ambient temperature of 21 °C, an air flow of 0.1 m s<sup>-1</sup>, and a relative humidity of less than 50% [2]. Thermal comfort is a psychological state of satisfaction with the ambient temperature, that is, a state in which it is neither too cold nor too hot. As this is a subjective feeling associated with a person's response to the environment, such as sensations of cold or heat, quantitatively defining thermal comfort is challenging [6]. Since the body surface area is most sensitive to environmental changes, wind speed, humidity, thermal radiation, and other environmental factors can affect the amount of body heat loss. Therefore, body surface temperature should be considered an important parameter for assessing the level of thermal comfort in humans [7]. A sense of comfort is related to gender, body mass index (BMI), age, activity level, and garment [7, 8]

Li et al. analysed heat transfer through multilayer garment systems that have a layer of corrugated geometry and different air permeability levels of materials. The aim was to establish how the combination of corrugation and permeability affects thermal insulation and the overall effect on heat transfer. The results showed that

heat drainage is more efficient in corrugated forms than in flat configurations. Moreover, the thermal flux decreased as permeability increased until a critical minimum was reached, after which the thermal flux started to rise sharply [9].

Testing the thermal properties of garment requires a comprehensive approach, including analysis of several interconnected thermal and physiological parameters. Despite significant progress in the development of measuring instruments and methods, further improvement is still needed. A particular challenge is the integration of different measuring systems and methods to enable simultaneous monitoring of several thermal and physiological characteristics, which would provide a more realistic view of the interaction between the body, garment, and the environment. Therefore, an integrated measuring system for evaluating the thermophysiological properties of garment was developed, installed, and patented at the *Faculty of Textile Technology* in the *Laboratory for Thermal Insulation Properties of Clothing*. The integrated system consists of five measuring methods and devices: hot plate, multipurpose differential conductometer, thermal mannequin, device for measuring temperature gradients, and device for measuring physiological parameters of the human body for precise evaluation of the thermal comfort of clothing. The integrated system have been developed, calibrated, patented [10]. The thermal properties of PGS on a thermal mannequin were investigated in this paper. Although numerous studies examine thermal comfort or thermal resistance of individual textile layers, there is a lack of system-level analyses that quantify the incremental contribution of removable thermal inserts relative to the outer shell under controlled dynamic conditions. Existing

research typically relies on single-method measurements, which do not capture interactions between layers during motion nor the redistribution of heat and air within multilayer clothing systems. For this reason, the thermal properties of complete PGS were investigated, with emphasis on understanding how differences in insert architecture (fleece and spacer) influence overall insulation when combined with an identical laminated outer shell.

## 2. Measurement system and materials

A segmented metal mould, anatomically designed to simulate the human body and known as the thermal mannequin, consists of 24 human body segments with builtin electric heaters, temperature sensors, 14 microcontroller interfaces, and a pneumatic system for arm and leg movements (Fig. 1).

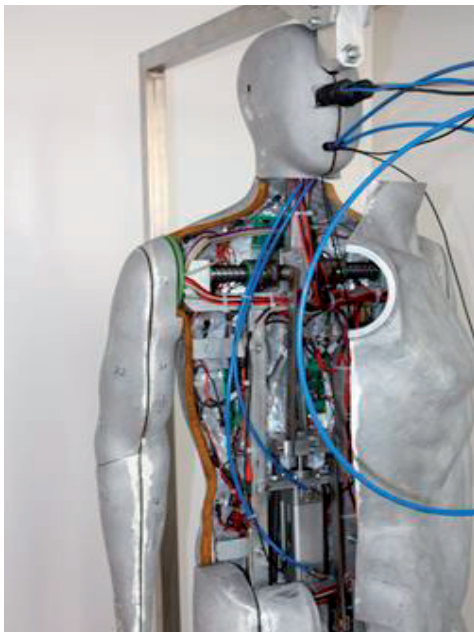


Fig. 1. Thermal mannequin [11]

The thermal mannequin shown in Fig. 1 is designed and installed at the Faculty of Textile Technology and forms part of a fully integrated measurement system comprising several unique devices for testing the thermal insulation properties of garment. All devices have been developed and patented by scientists from the Faculty.

The thermal mannequin [11] is installed in the thermal insulation chamber, and software is used to manage the mannequin (selection of segments and determination of the temperature of individual segments), measure the thermal properties of garment on the mannequin, and control the air conditioning chamber (setting the environmental temperature, air flow rate, and monitoring atmospheric humidity) (Fig.2).

For each sample, measurements were taken over a 20-minute period, with readings recorded every 5 seconds, resulting in 240 data points per sample, which were then av-

eraged to obtain the mean thermal insulation. Before the measurements began, the samples were placed in the thermal insulation chamber containing the thermal manikin and stabilised under the same ambient conditions (temperature, air velocity, humidity) as the thermal manikin.

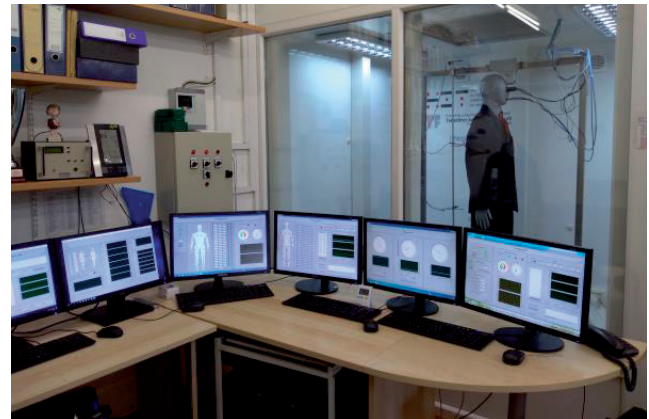


Fig. 2. Thermal mannequin installed in the thermal insulation chamber and computer software displays

The thermal mannequin is used to obtain static and dynamic measurements consistent with the simulation of human walking. Once garment is placed on the thermal mannequin, its thermal properties under dynamic conditions are determined in a manner that simulates the wearer's gait, with both arms and legs moving in opposite phases. The limbs are moved using a pneumatic linkage system integrated into the thermal mannequin. The movement speed of the limbs can be varied over a wide range and precisely adjusted by the air damper to achieve a movement speed of  $45 \pm 2$  double steps per minute and  $45 \pm 2$  double arm movements per minute for walking, in accordance with the standard EN ISO 15831:2004. The method for controlling, regulating, measuring, and calculating the thermal systems on the garment was introduced using a segmented metal casting modelled after the human body, with the capability to activate and deactivate all segments (of the entire casting) or any group of segments, and to introduce and set measurement parameters in accordance with standards for experimental research. When stable environmental conditions (temperature, relative humidity, and air velocity) are achieved in the climatic chamber, the value of the device constant for the thermal mannequin should be determined, and can be obtained according to the following equation [12]:

$$R_{ct0} = \frac{(T_s - T_a) \cdot A}{H_0}$$

where:  $R_{ct0}$  – resultant total thermal insulation of the measuring device, including the thermal insulation of the boundary air layer,  $m^2K W^{-1}$ ;  $A$  – total surface area of thermal manikin,  $m^2$ ;  $T_s$  – mean skin surface temperature of thermal manikin,  $^{\circ}C$ ;  $T_a$  – air temperature within the climatecontrolled chamber,  $^{\circ}C$ ; and  $H_0$  – total heating power supplied to the thermal manikin,  $W$

The evaluation of the thermal properties of the garment using the thermal manikin is performed by placing the selected garment or ensemble around its body in either static or dynamic mode. In dynamic measurement, the thermal manikin simulates the wearer walking, with both the legs and arms moving in phase reversal, at a specified number of movements per minute and a specified stride length. The measurements can be performed under static or dynamic environmental conditions simulated in the climatic chamber. After determining thermal comfort, indicated by the stabilisation of parameter values (numerical and shown in diagrams), measurements are taken and the thermal insulation is calculated using following equation [12]:

$$R_{ct} = \frac{(T_s - T_a) \cdot A}{H} - R_{ct0}$$

where: H – location where the electrical power required to maintain the temperature of the measuring surface on which the measurement sample is positioned is provided.

Technical characteristics of the builtin materials for the outer shell and removable thermal insert are presented in **Table 1**.

Protective garments system (jacket) made of outer shell and removable thermal insert (**Fig.3**).



**Fig. 3.** Model sketch of protective garment system: a) outer shell (IM1+IM2); b) removable thermal insert (TU1: IM3+IM4 and TU2: IM3+IM5)

**Table 1.** Review of the analysed technical characteristics of the sample of builtin material.

Technical characteristics	Material	Value
Raw material composition	IM1	PES 100%
	IM2	PES 100%
	IM3	PES 100%
	IM4	PA 100%
	IM5	PES 100%

Technical characteristics	Material	Value
Mass per unit area	IM1	168.90 gm <sup>2</sup>
	IM2	54.60 gm <sup>2</sup>
	IM3	298.80 gm <sup>2</sup>
	IM4	231.00 gm <sup>2</sup>
	IM5	76.8 gm <sup>2</sup>
Water vapor permeability	IM1	3135.7 gm <sup>2</sup> 24h <sub>1</sub>
	IM2	3469.70 gm <sup>2</sup> 24h <sub>1</sub>
	IM3	4341.80 gm <sup>2</sup> 24h <sub>1</sub>
	IM4	3648.30 gm <sup>2</sup> 24h <sub>1</sub>
	IM5	4500 gm <sup>2</sup> 24h <sub>1</sub>
Air permeability	IM1	mean value: 0.036 m <sup>3</sup> m <sup>2</sup> min <sup>-1</sup> min <sup>-1</sup> from right side to reverse side: 0.007 m <sup>3</sup> m <sup>2</sup> min <sup>-1</sup> from reverse side to right side: 0.064 m <sup>3</sup> m <sup>2</sup> min <sup>-1</sup>
	IM2	expressive
	IM3	mean value: 19.33 m <sup>3</sup> m <sup>2</sup> min <sup>-1</sup> from right side to reverse side: 19 m <sup>3</sup> m <sup>2</sup> min <sup>-1</sup> from reverse side to right side: 19.66 m <sup>3</sup> m <sup>2</sup> min <sup>-1</sup>
	IM4	expressly
	IM5	mean value: 4.03 m <sup>3</sup> m
		'min' from right side to reverse side: 3.91 m <sup>3</sup> m <sup>2</sup> min <sup>-1</sup> from reverse side to right side: 4.15 m <sup>3</sup> m <sup>2</sup> min <sup>-1</sup>
Raw material composition of the membrane	IM1	PU 100%

For the protective garments system PGS1.1, the following embedded materials have been selected:

- for the outer shell (OS1) as the outer layer, a laminated fabric with a PU membrane labelled IM1 was chosen, and for the lining material, a mesh polyester lining labelled IM2.
- for the removable thermal insert (TU1), the polyester fleece material labelled IM3 (on the outside of the removable thermal insert) and the polyamide spacer material labelled IM4 (on the inside of the removable thermal insert) were selected

For protective garments system PGS1.2, the following embedded materials have been selected:

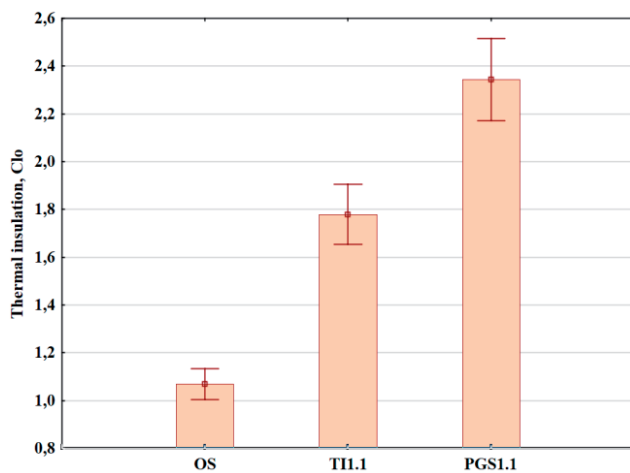
- for the outer shell – as in PGS1.1.
- for the removable thermal insert (TU2), the polyester fleece material labelled IM3 (on the outside of the removable thermal insert) and the lining material labelled IM5 (on the inside of the removable thermal insert) were selected

It is important to emphasise that mesh lining IM2 and spacer material IM4 are fabrics with large interyarn openings, resulting in very high air permeability (expressive). They do not function as air barriers and contribute negligibly to system level thermal insulation. Their purpose in the PGS is aesthetic, to cover seams and protect the removable insert surface, not thermal.

### 3. Results

When measuring thermal insulation, the temperature of the heated surfaces of the models was 34.0 °C and the ambient temperature was 20 °C. The airflow rate in the chamber was 0.4 m s<sup>-1</sup> and the relative humidity was 32%. The measured total thermal insulation in static mode of the undressed model, together with the boundary layer of air adjacent to the surface ( $R_{ct0}$ ), was 0.09116 m<sup>2</sup> K W<sup>-1</sup>.

A graphical representation of the results is shown in **Fig. 4** and **Fig. 5**.



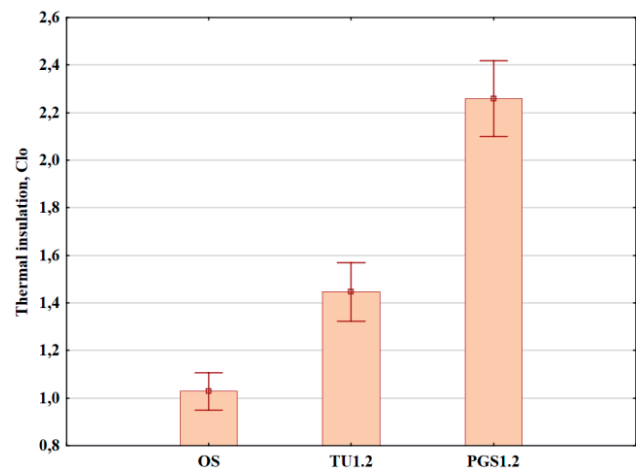
**Fig. 4.** Graphical representation of measurement results of thermal insulation in static mode of the outer shell (OS), removable thermal insert TII.1, and protective garments system PGS1.1

Based on the measured data set, the thermal insulation of the outer shell is at the basic level, as in the protective garments system PGS1.1, because the same outer shell was used, with a thermal insulation value of 1.03 Clo (**Fig. 4**). The thermal insulation of the removable thermal insert is 1.78 Clo. The thermal insulation value of the protective garments system PGS1.2 is 2.36 Clo.

Based on the measured data set, a graphical representation of the results was produced, showing that the thermal insulation of the outer shell is at a basic level of 1.03 Clo (**Fig. 5**). The thermal insulation of the removable thermal insert is 1.45 Clo thus providing adequate protection against cold. The thermal insulation value of the protective garment system, created by combining the outer shell OS1 and the removable thermal insert TUI, is 2.26 Clo.

In **Fig. 4** and **Fig. 5**, a sharp increase in thermal insulation values is observed when the outer shell is combined with the heat insert.

The research confirms that removable thermal inserts are the main contributors to the thermal insulation of protective garments system, while the outer shell plays a secondary role, primarily providing protection against wind and moisture. Measurements conducted on a thermal mannequin under controlled environmental conditions showed that combining an outer shell with a removable thermal insert significantly increases the overall thermal insulation of the protective garments system. Specifically, the protective garments system PGS1.1, which includes a removable thermal insert (TUI) made of polyester fleece material labelled IM3 (on the outside of the insert) and polyamide spacer material labelled IM4 (on the inside of the insert), was selected and achieved a thermal insulation of 2.36 Clo. PGS1.2, with a removable thermal insert (TU2) made of polyester fleece material labelled IM3 (on the outside of the insert) and lining material labelled IM5 (on the inside of the insert), was also selected and reached 2.26 Clo.



**Fig. 5.** Graphical representation of measurement results of thermal insulation in static mode of the outer shell (OS), removable thermal insert TII.2, and protective garments system PGS1.2

Based on a oneway numerical analysis of variance (ANOVA), no statistically significant difference was found between the results for PGS 1.1 and PGS1.2. These results suggest that the values for the two groups do not differ significantly, indicating a similar level of variability within the analysed data.

### 3. Discussion

The measured differences in systemlevel insulation can be explained by how the removable inserts manage air and convection within the clothing assembly. Both the fleece and the spacer introduce a thicker region of relatively quiescent air, which is the main contributor to thermal resistance. Their porous microgeometries interrupt bulk airflow and reduce convective coupling between the skin-side and shellside microclimates, so insulation remains high even when the wearer's motion is simulated on the thermal manikin. The laminated outer shell, common to

both systems, primarily stabilises the external boundary layer as a wind and moisture shield; by itself, it does not provide an air volume comparable to that created by the inserts. The mesh lining, with large apertures and very high air permeability, does not act as a wind barrier and adds negligible resistance; it is present for constructional and aesthetic reasons, chiefly to cover seams and protect the insert surface. These mechanisms are consistent with the presented results: the shell alone provides a lower Clo, while combining the shell with either insert raises the overall insulation to the observed system values, with only a small difference between the fleece- and spacerbased variants within the measured variability.

#### 4. Conclusion

The research confirms that removable thermal inserts are the main contributors to the thermal insulation of protective garments system, while the outer shell plays a secondary role, primarily providing protection against wind and moisture. Measurements conducted on a thermal insulation of the protective garments system. Specifically, the protective garments system PGS1.1, which includes a removable thermal insert made of a combination of fleece material and spacer material, achieved a thermal insulation of 2.36 Clo, while PGS1.2, with a removable thermal insert made of a combination of fleece and lining material, reached 2.26 Clo. Measurements of the thermal insulation of protective garments system on a thermal mannequin in controlled environmental conditions showed that combining an outer shell with a removable thermal insert significantly improves thermal insulation. It can be concluded that adding removable thermal inserts to protective clothing can more than double its thermal insulation. Given that the cost of removable thermal inserts is significantly lower than that of the outer shell, their use in protective clothing is also highly justified from a cost perspective. Specifically, the protective garments system PGS1.1, which includes a removable thermal insert made of a combination of fleece material and spacer material, achieved a thermal insulation of 2.36 Clo, while PGS1.2, with a removable thermal insert made of a combination of fleece and lining material, reached 2.26 Clo. Measurements of the thermal insulation of protective garments system on a thermal mannequin in controlled environmental conditions showed that combining an outer shell with a removable thermal insert significantly improves thermal insulation. It can be concluded that adding removable

thermal inserts to protective clothing can more than double its thermal insulation. Given that the cost of removable thermal inserts is significantly lower than that of the outer shell, their use in protective clothing is also highly justified from a cost perspective.

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