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Impact of Clothing Size on Thermal Insulation – A Pilot Study

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Abstract
Thermal insulation may be influenced by the size of clothing and thus the volume of air gaps. The aim of this study was to determine the relationship between the size of outer wear clothing, and thus the indirect fit (the volume and size of air gaps), and thermal insulation in static and dynamic conditions. A set of underwear and two types of outerwear for workers of the energy sector and the chemical industry were selected for the study. Results showed that the value of thermal insulation (regardless of the type of outerwear) first increased with increasing clothing size.

Keywords
thermal insulation, air gaps, air volume, 3D scanning.

Introduction

The thermal insulation of clothing affects the heat exchange between a human and the environment. The size of clothing, and therefore the indirect garment fit to the human body, affects the insulation, and thus the amount of heat "escaping" from the organism to the environment.

Heat transfer through clothing is influenced by many factors, inter alia: the type of material and specific design [1,2]. These factors, according to Špelić et al. [1], determine the degree of fitting the garment to the body shape, while creating a non-homogeneous air layer under the clothing. Many researchers have noted that the size of the air volume under clothing (resultant air volume) is the key parameter which determines their thermal insulation [3,4,5].

It was observed that thermal insulation increases linearly with air gap sizes until there is heat transfer by convection [6,7]. The heat exchange in the air gap can take place by radiation, conduction or convection in dependence on the size of the air gaps [8,9]. Thermal conductivity and radiation are the basic methods of heat transfer in a smaller air gap, and the thermal insulation increases with the size of the air [9,10]. On the other hand, when the size of the air gaps is too large due to convective heat transfer [9,11,12,13], the insulating effect of the air gaps would be weakened [9,14,15,16].

However, as noted by Špelić et al. [1], the distribution and size of the air volume can be confusing. The air gaps were not evenly distributed over the manikin and were dependent on the clothing style and fit as well as on the body shape [17].

Based on the results obtained, Lu et al. [18] found that the value of the total air volume under the garment was one of the parameters determining air gaps, and this value (total air volume) may provide useful information for the assessment of garment fit.

Air gaps or the total air volume can be determined using the 3D scanning technique, which is considered the most accurate and reproducible method for air volume quantification under clothing [7,19,20].

The aim of this study was to determine the relationship between the size of outer wear clothing, and thus the indirect fit (the volume and size of air gaps), and thermal insulation in static and dynamic conditions. A 3D scanning technique was used to calculate/measure the total air volume of air under the clothing.

A set of underwear (U) and two types of outerwear for workers of the energy sector (S1) and the chemical industry (S2) (3 sizes according to the manufacturer's markings) were selected for the tests.

1. Material and methods

1.1. Materials

One type of underwear (U) and two types of outerwear intended for workers of the energy sector (S1) and the chemical industry (S2) were used for the tests. The tested clothing items are shown in Figure 1.

A detailed description of the clothing used in this study, in terms of material composition and normative requirements, is included in Table 1.

In order to investigate the influence of the size of outerwear on thermal parameters, one size of underwear (size 54) and three sizes for outerwear (size: 50, 54 and 56) were chosen. These sizes were selected in terms of the dimensions of the thermal manikin [28,29]. Detailed data obtained from the manufacturer, describing the above-mentioned sizes, are presented in Table 2.

1.2. Equipment

1.2.1. Thermal manikin.

A Newton-type thermal manikin (Measurement Technology Northwest, USA) consisting of 34 segments was used for the tests. A detailed description of the manikin was included in previous publications [28,29].

Fig.1. The clothing used for the tests: a) underwear (U), b) set 1 (S1) (energy sector), c) set 2 (S2) (chemical industry)

1.2.2. Climatic chamber.

The tests of thermal parameters of the clothing were carried out in a controlled manner in a climatic chamber (Weiss, type WK23 ‘) [30].

1.2.3. Microclimate meter.

For additional control of research conditions, a thermal comfort data logger 1221 INNOVA was used during the tests.

1.2.4. 3D scanner.

In order to determine the air volume, an iPad tablet was used (model number: MUQX2FD/A, software version 15.0) with a dedicated scanning adapter (MARK II sensor with model number ST02A v1.2, firmware 1.0.1).

1.3. Methods

1.3.1. Thermal insulation.

Thermal insulation tests were conducted both in static (total thermal insulation (I_t)) and dynamic conditions (resultant total thermal insulation (I_{tr})). The tests were carried out in accordance with the assumptions of the EN 342:2018 [33] and EN ISO 15831:2004 [34] standards. The tests were performed on a thermal manikin dressed in specialist skin. Thermal insulation calculations were made according to the parallel model calculation [28,29]. At least two repetitions were performed. For one type of outerwear, three configurations were assigned in accordance with the notation (used below in the article): U_S1or S2 (outerwear size: 50, 54, 56) (e.g. U_S1(50)).

1.3.2. Total air volume.

The total air volume was determined using a 3D scanner. The provisions of the EN ISO 20685-1:2019-01 standard [31] were used for these tests. A detailed description of the research is provided in [32]. Each set of clothing was scanned two times. Blender 3D graphics software was used for computer calculations.

Two values of the total air volume were determined: for the entire set of garments (V_{t_B+Z}), and for the underwear only V_{t_B}, as shown in Figure 2.

For the analysis conducted, it was assumed that after putting the outerwear on the manikin, the position of the underwear in relation to the surface of the manikin did not change.

Name		Material composition	Normative requirements	Industrial application
Outerwear clothing				
Set S1	jacket and waist-length pants	79% cotton, 20% polyester, 1% antistatic fiber; Hydro-Tec finish; 260 g/m²	EN ISO 13688:2013 [21], EN ISO 11611:2015 [22], EN 11612:2015 [23], EN 1149-5:2018 [24], EN 13034:2005 [25], EN ISO 14116:2015 [26], IEC 61482-2:2018 [27]	power industry, chemical industry, welding and hot factors, explosion hazard zone, high visibility
Set S2	acid-proof jacket and acid-proof dungarees	80% polyester, 20% cotton; 225 g/m²	EN ISO 13688:2013 [21], EN 13034:2005 [25]	chemical industry
Underwear				
U	long-sleeved t-shirt and underpants	59% Protex, 39% Cotton, 2% negastat; 205 g/m²	EN ISO 13688:2013 [21], EN ISO 11612:2015 [22], EN 1149-5:2018 [24]	gas industry, fuel industry, explosion hazard zone

Table 1. A detailed description of the tested clothing

Size	Height [cm]	Circumference		
		chest [cm]	waist [cm]	collar [cm]
50	170-176	96-100	88-92	40-41
54	176-182	104-108	96-100	42-43
56	182-188	108-112	100-140	43-44

Table 2. Data obtained from the manufacturer describing the different sizes

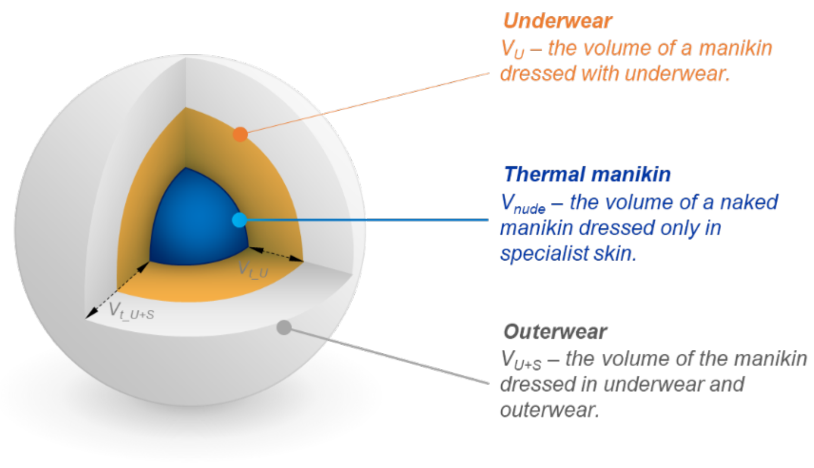

Fig.2. Method of calculating the total air volume schematically presented

2. Results

2.1. Thermal insulation

The thermal insulation of the nude manikin wearing only the special skin (thermal insulation of boundary air layer) amounted to the and resultant thermal insulation, respectively: 0.104 m²°C/W and 0.088 m²°C/W. The underwear (with specialized skin) used for the tests was characterized by a total and resultant thermal insulation, respectively, at the level of 0.164 ± 0.001 m²°C/W and 0.131 ± 0.000 m²°C/W (Table 3).

The results of the total thermal insulation for clothing sets S1 and S2, depending on their size, were in the range 0.202 - 0.217 m²°C/W for static conditions (I_t) and 0.160 - 0.172 m²°C/W for dynamic (I_{tr}) conditions (Table 3).

In order to check whether the results obtained differ significantly from each other, the percentage of the difference between the results obtained was calculated according to the formula (1):

$$D_i\% = 100\,\frac{(x_{larger\_size} - x_{smaller\_size})}{x_{larger\_size}}\ [\%] \qquad (1)$$

where: $D_i\%$ - the percentage difference between the measurements, $x_{smaller\_size}$ - the value obtained for the smaller of the sizes compared, x_{larger_size} - the value obtained for the larger of the sizes compared.

The values obtained were compared with the 4% permissible measurement error (EN 342:2018; EN ISO 15831:2004) [33,34]. The calculated percentage of the difference between the results obtained for static and dynamic conditions is shown in Figure 3.

The results obtained were within the permissible 4% measurement error.

2.2. Total air volume V_t

Using the analysis of the 3D scans made and dedicated software, the total volume

Variants	Size	V_t [dm³]	d_{air} [mm]	Total thermal insulation I_t [m²°C/W]	Resultant total thermal insulation I_{tr} [m²°C/W]
U	54	16	10	0.164±0.001	0.131±0.000
U_S1(50)	50	34	21	0.204±0.001	0.166±0.000
U_S1(54)	54	39	29	0.210±0.001	0.172±0.000
U_S1(56)	56	47	30	0.217±0.000	0.169±0.000
U_S2(50)	50	34	21	0.202±0.000	0.160±0.000
U_S2(54)	54	48	24	0.205±0.002	0.164±0.000
U_S2(56)	56	50	29	0.209±0.000	0.165±0.000

Table 3. Air volume, air gap size, total thermal insulation (mean value ± standard deviation) calculated by parallel method for static and dynamic test conditions

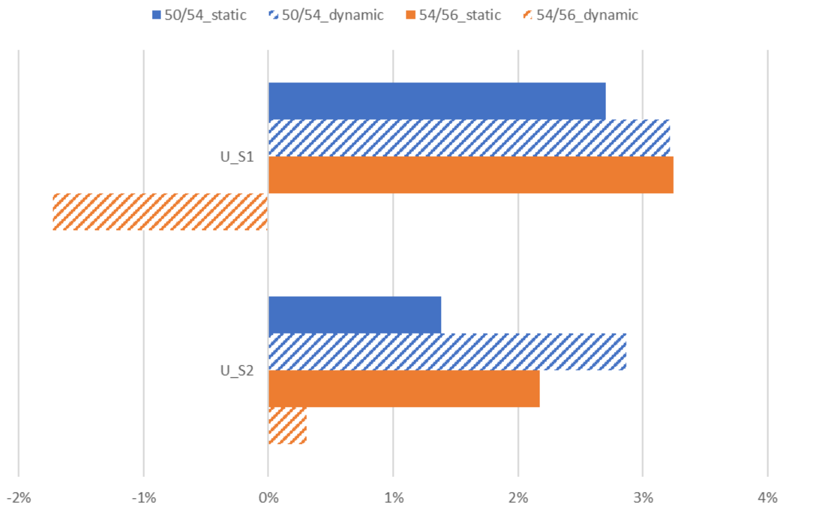

Fig.3. Percentage of the difference between the values of thermal insulation (in static and dynamic conditions) for individual sizes of outerwear (parallel method)

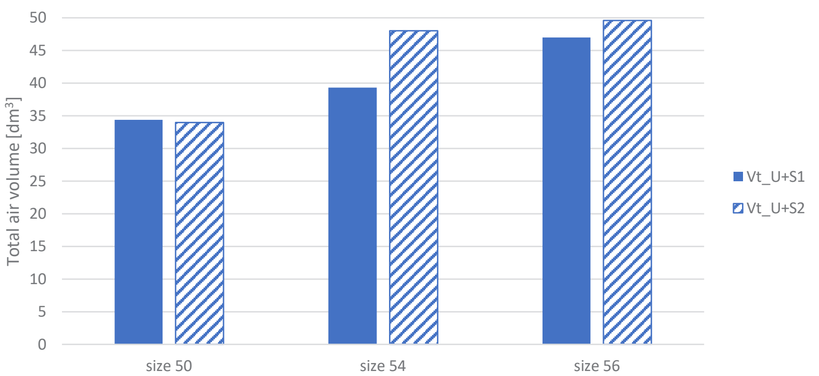

Fig.4. Total air volume: from the skin of the manikin to the surface of the outerwear (V_{t_U+Si})

of a nude manikin dressed in specialist skin was determined (V_{nude} = 71.0 dm³). The total volume of the dressed manikin with underwear was V_U = 86.8 dm³. On the basis on the scans obtained of the manikin dressed in the whole set of clothes, the total air volume was calculated: from the manikin's skin to the outerwear surface (V_{t_U+Si}). The values obtained are given in Figure 4.

The larger the outerwear size, the greater the air volume observed. The distribution of air volume in three different sizes is presented for the example of the S2 scans obtained (Figure 5).

As shown in Figure 5, the orange surface denoted the manikin dressed in special skin and underwear, and the black grid of points denoted the outer wear clothing. The best fit to the surface of the underwear was mainly on the upper-trunk segment.

Air gaps. Based on the total air volume obtained for the dressed and nude manikins, the average air gap size/ distance d_{air} was defined. It was calculated according to the Equation 2 [35]:

$$d_{air} = \frac{V_{t\_U+Si}}{SA_{nude}} \cdot 10 \qquad (2)$$

where: d_{air} - the average distance between the base layer/nude manikin and the last clothing layer [mm], V_{t_U+Si} - the total volume of the clothed manikin minus the volume of the base layer/nude manikin [cm³], SA_{nude} - the surface area of the nude manikin [cm²].

The values obtained are summarized in Table 3.

2.3. The relationship between the total air volume and the value of thermal insulation

The relationship between the clothing's total thermal insulation (static and dynamic), its air volume, and average air gaps is presented in Figures 6-7.

To ensure that the total thermal insulation equals that of the boundary

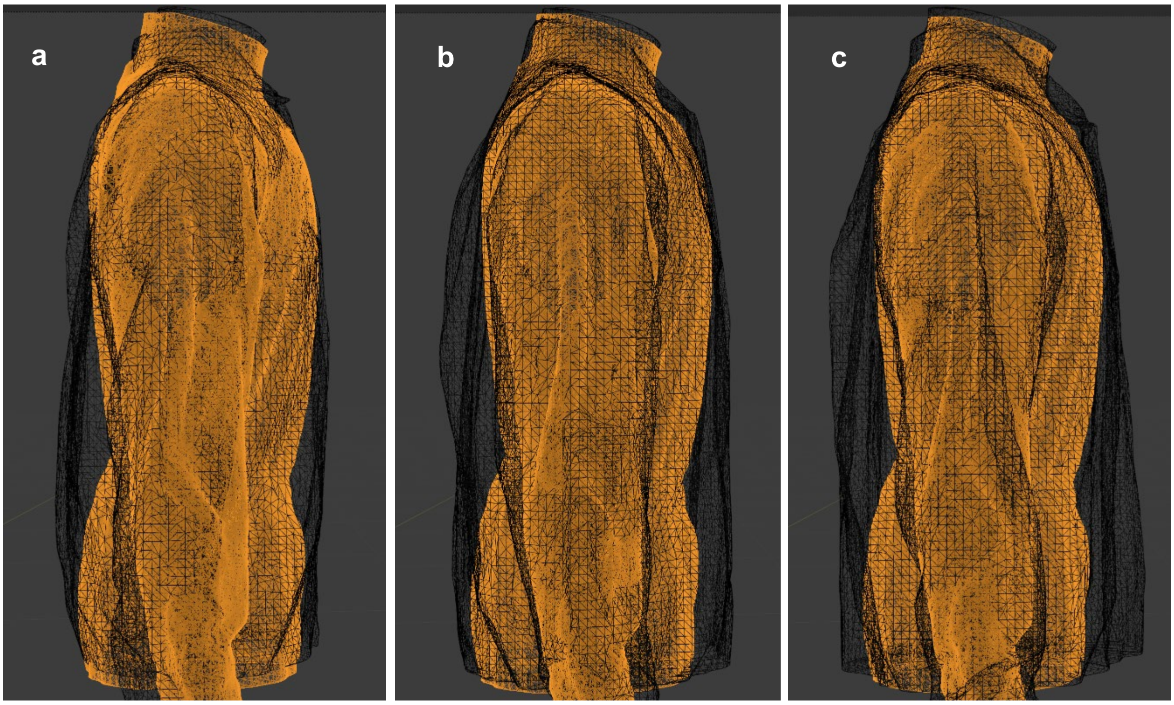

Fig.5. 3D scan images of manikin dressed with underwear and set S2 in different variants: a) size 50), b) size 54, c) size 56

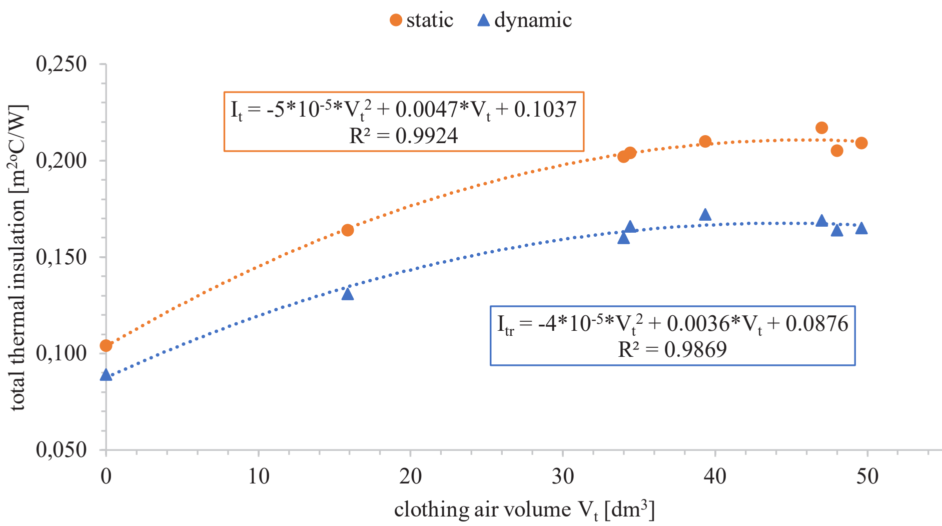

Fig.6. Relationship between the clothing's total thermal insulation (static and dynamic) and air volume

air layer (i.e., for static and dynamic conditions: 0.104 m^2°C/W and 0.088 m^2°C/W, respectively) when no clothing layer is present, the regression equation was forced to go through the point (for static and dynamic test conditions 0, 0.104 and 0, 0.088, respectively). The coefficient factor R^2 was higher than 0.99 for both parameters. The equations can be found in Table 4.

3. Discussion

Based on the results obtained, it can be concluded that set S1 was characterized by a higher thermal insulation value compared to set S2. They were made of a mixture of cotton and polyester, but in different proportions. S1 was 80% cotton and S2 - 80% polyester. Also, the weight of the S1 set was higher than that of the S2 clothing. Despite the more extensive structure of the S2 (garment dungarees were used), the S1, made mainly of cotton, was characterized by a higher thermal insulation value.

The garments fit may affect the thermal insulation. In present study, the value of thermal insulation (regardless of the type of outerwear), increased with the size of clothing. The results obtained were consistent with other results, where thermal insulation was better in looser garments than in tight-fitting ones

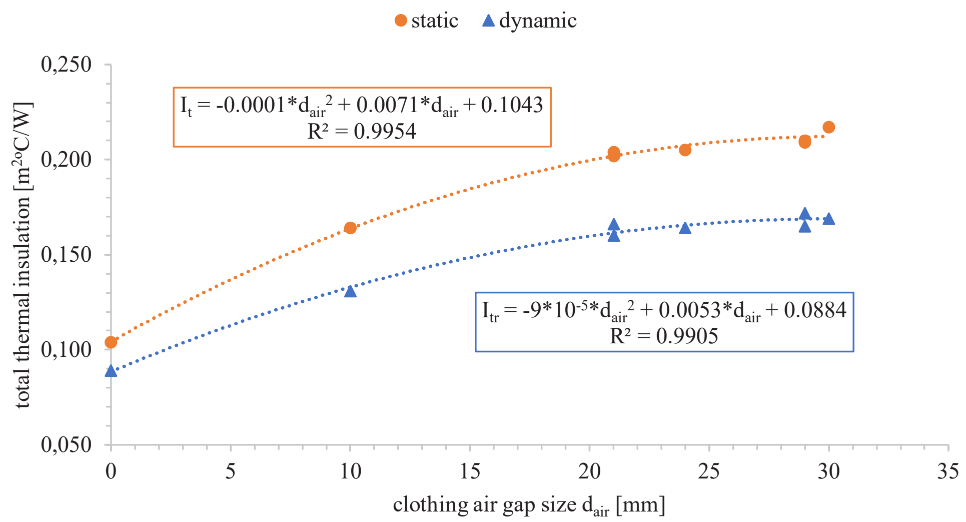

Fig.7. Relationship between the clothing's total thermal insulation (static and dynamic) and the air gap size

Test conditions	Total air volume V_t [dm³]	Average air gap d_{air} [mm]
static	$I_t = -5*10^{-5}*V_t^2 + 0.0047*V_t + 0.104$ (2)	$I_t = -0.0001*d_{air}^2 + 0.0071*d_{air} + 0.104$ (3)
dynamic	$I_{tr} = -4*10^{-5}*V_t^2 + 0.0036*V_t + 0.088$ (4)	$I_{tr} = -9*10^{-5}*d_{air}^2 + 0.0053*d_{air} + 0.088$ (5)

Note: I_t – the clothing's total thermal insulation [m²°C/W], I_{tr} – the clothing's resultant total thermal insulation [m²°C/W]

Table 4. The equations for the relationship between the clothing's total thermal insulation (in static and dynamic test conditions), total air volume (V_t), and air gap size (d_{air})

[36,37]. However, in the case of dynamic tests for S1, the value of the resultant total thermal insulation was the highest for size 54. In the case of S2, the values for sizes 54 and 56 were similar. The reasons for the differences between these results in dynamic conditions were sought in the construction of the clothing. The S1 set consisted of a jacket without any ribbing, while the S2 set (unlike the S1), consisted of dungarees, and the jacket and sleeves were finished with ribbons. This solution allowed for limited movement of the spaces filled with air under the clothing while simulating the manikin walking (under dynamic conditions). According to other researchers [38,39], if the garment size is the same, the fabric properties (e.g. drape, rigidity and weight) may impact air gap sizes. Larger air gaps were observed in thicker and stiffer clothing [38], which could have an influence on the total thermal insulation value.

Based on the 3D scans performed, the total air volumes under the clothing were determined. The air volume for sets S1 and S2 were in the range of 34-47 dm³ and 34-50 dm³, respectively. The test results were compared with the total volume of air spaces obtained from thermal scanning of one-piece work suits. According to Lu et al. [18] the total air volume for the tested single-layer suit ranged from 35 to 60 dm³. Ke and Wang [36] tested five different multilayer ensembles, where their total air volume was in range c.a. 46 – 74 dm³. These values coincide with the results obtained in the present research, which indirectly confirms the correctness of the measurements taken.

There are many factors which influence the air gape size. Some such are garment properties fit and style [40]. In the present study, an increase in air gap size was observed as the clothing size increased, which is consistent with other studies [3,39,41]. However, in the case of loose-fitting garments, the differences for the S2 set between sizes 54 and 56 were small in terms of the total volume of the air spaces. The smaller increase in air gap size in set S2 may have been due to the different garment design (dungarees in this case), which was also confirmed by others [36,40,42]. Ke and Wang [36] observed a decrease in air gaps on the abdomen and back when waist belts were used. According to Frackiewicz-Kaczmarek et al. [3], air gap thickness/size was changed mostly at the lower trunk depending on the clothing fit; but not at the upper trunk. This may be due to differences in the way the garment falls onto /or aligns with various areas of the body [3]. The same conclusions were drawn from the results presented (3D scan images – Figure 5). Therefore, when analyzing the results of the total air volume and air gap sizes obtained, attention should also be paid to the construction and the way the garments fits on the manikin.

Based on the results obtained, it is concluded that the relationship between the calculated total air volume or the air gap size and the thermal insulation of the tested sets of clothing (both in static and dynamic conditions) can be written as a quadratic polynomial. The correlation between the air gap volumes and thermal insulation of clothing was also observed by others [36,38,39]. Ke and Wang [36] also read the relationships mentioned above as a quadratic function. After the initial increase in thermal insulation with increasing air gap sizes, a decrease in the thermal insulation was observed above a certain size of clothing/air gaps [36,38,39]. The lack of a linear increase in thermal insulation and clothing size was most likely due to the fact that air gaps reached the size/volume where natural convection began and air circulation in the microclimatic air layers occurred [36,38,39]. It was observed that natural convection emerged when the air gap thickness was higher than 10 mm, or when the air gap volume was greater than 6 dm^3 [38]. In another study, when the air gap volume was 11.9 dm^3, the thermal insulation decreased [39]. In the present studies, a decrease in thermal insulation was observed above 47 dm^3 and c.a. 36 mm for the air volume and air gap size. In turn, Ke and Wang [36] observed that the limit value of air gaps above which the thermal performance decreased was 55.8 dm^3 and 37.8 mm for the volume and size, respectively. However, it should be emphasized that these observations mostly concerned single-layer garments.

4. Conclusions

In present study a set of underwear (U) and two types of outerwear for workers of the energy sector (S1) and the chemical industry (S2) (three sizes according to the manufacturer's markings) were investigated. The results demonstrated the impact of air gaps on the thermal property of clothing.

The obtained results demonstrated that at the beginning the value of thermal insulation (regardless of the type of outerwear) increased with the size of clothing, reaching a certain value of air gaps. It was found that the turning points (from which the values decrease) calculated by regression equations were 47 dm^3 and c.a. 36 mm for the air volume and air gap size respectively. It should also be noted that the present study conducted on multi-layer clothing may initiate further work on multi-layer clothing. Until now, the air gap has mostly been tested in one-layer clothing; sometimes only for the upper or lower body [3,7,40,41,42,43]. The present studies could be inspiration for further research on multi-layer clothing as an analysis of a whole set. The authors were also aware of the limitation of this study, e.g. an analysis of the relationship between the size of the air gaps and the location on the body was not performed; but all limitations will be reduced in future research.

Declaration of Conflicting Interests

The Authors declare there is no conflict of interest.

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