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Influence of Air Velocity on the Total Thermal Insulation of Different Types of Clothing

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Abstract
According to the standards describing research on the total and resultant thermal insulation [1-3], the requirements for the microclimate in which tests are performed must be recorded. However, these values are given with uncertainty. According to the EN ISO 15831 [1] and EN 342 [2] standards, air velocity should be set to (0.4 ± 0.1) m/s. For this reason, it is necessary to verify to what extent values exceeding the said range affect the results of the thermal insulation. Research was carried out for 3 sets of clothing differing in the number of layers of the material. The influence of air velocity on clothing thermal insulation was examined with three values of V_a: 0.4 m/s, 0.8 m/s and 1.2 m/s. Correction factors (CFs) were calculated and compared with the CF values set out in the EN ISO 9920 standard [3].

Key words: *thermal manikin, thermal parameters, air velocity, thermal insulation.*

Introduction

The use of thermal manikins for evaluation of clothing thermal insulation is laid down in detail in the standards [1-3] and in a number of scientific articles [4-11].

According to the standards describing research on the total and resultant thermal insulation [1-3], the requirements for the microclimate in which tests are performed should be recorded. However, these values are given with uncertainty. According to the EN ISO 15831 [1] and EN 342 [2] standards, air velocity should be set to (0.4 ± 0.1) m/s. For this reason, it is necessary to verify to what extent values exceeding the said range affect the results of the thermal insulation.

Thermal insulation

According to EN ISO 15831 [1] and EN 342 [2], the testing of clothing thermal insulation should be carried out in a climatic chamber with a thermal manikin. Thermal insulation was measured using a heat exchange mode with a constant surface temperature of the manikin equal to 34 °C and variable power delivered to each segment of the manikin.

Given the division of the manikin into segments, two calculation methods of clothing thermal insulation (I_t) were applied: the serial model ***Equation (1)*** and the parallel model ***Equation (2)*** [1].

$$I_t = \sum_1^n f_i \left[\frac{(t_{si} - t_a) \times a_i}{H_{ci}} \right] \quad (1)$$

$$I_t = \frac{(t_s - t_a) \times A}{H_c} \quad (2)$$

where:
t_{si} – temperature on surface of *i*-segment of manikin, °C;
t_s– mean temperature on surface of manikin, °C;
t_a – air temperature in climatic chamber, °C;
H_{ci} – sensible heat loss from *i*-segment of manikin, W;
H_c – total heat loss, W;
a_i – surface area of *i*-segment of manikin, m^2;
f_i – part of total surface area which contains *i*-segment of manikin, $f_i = \frac{a_i}{A}$ (3)
A – total surface area of manikin, m^2.

In the case of the serial model, the thermal insulation is determined as the sum of the insulations calculated for individual segments. In the case of the parallel model, thermal insulation is calculated as the value related to the whole manikin. Standard [1] assumes the occurrence of differences between the values determined in the serial and parallel models. The above-mentioned standards [1, 2] permit a 4% error between the tests for one set of clothing in one method of calculation.

Conditions during the thermal insulation test

The air temperature in the climatic chamber should ensure a heat flux on individual segments of at least 20 W/m^2 or a difference between the air temperature and surface temperature of the manikin of less than 12 °C [1]. Measurements of clothing thermal insulation should be performed in a steady state both in terms of the microclimate conditions (parameter values in the climatic chamber) and thermal manikin (values of surface temperature of the manikin and heat flux on individual segments).

Table 1. *Air velocity and relative humidity requirements set out in the standards [1-3].*

	EN ISO 15831 [1]	EN 342 [2]	EN ISO 9920 [3]
V_a m/s, air velocity	0.4 ± 0.1	0.4 ± 0.1	0.15
RH %, relative humidity	30-70 prefer 50	30-70 prefer 50	30-70 prefer 50

Table 2. *Corrective equations (without the influence of walking) according to EN ISO 9920 [3].* ***Note:*** *I_a – thermal insulation of boundary air layer, I_{cl} – intrinsic thermal insulation, I_t – total thermal insulation, I_{tr} – resultant total thermal insulation, corrI – correction factor, V_a – air velocity, p – air permeability.*

Thermal insulation, m^2 °C/W (clo)	Corrective equations	
I_{cl} = 0 (nude)	$I_{tr} = I_a = corrI_a \cdot I_{a,static}$ (4) $corrI_a = e^{\left[-0.533\cdot(V_a-0.15)+0.069\cdot(V_a-0.15)^2\right]}$ (5)	V_a (0.15-3.5 m/s)
0.186(1.2) < I_t < 0.310(2.0)	$I_{tr} = corrI_t \cdot I_t$ (6) $corrI_t = e^{\left[-0.281\cdot(V_a-0.15)+0.044\cdot(V_a-0.15)^2\right]}$ (7)	V_a (0.15-3.5 m/s)
I_t > 0.310 (2.0)	$I_{tr} = corrI_t \cdot I_t$ (6) $corrI_t = e^{\left\{\left[-0.0881\cdot(V_a-0.4)+0.0779\cdot(V_a-0.4)^2\right]\cdot p^{0.2648}\right\}}$ (8)	V_a (0.4-1.0 m/s) p (1 – 1000 l/(m^2·s))
I_t > 0.310 (2.0)	$I_{tr} = corrI_t \cdot I_t$ (6) $corrI_t = e^{\left\{\left[-0.0512\cdot(V_a-0.4)+0.794\cdot10^{-3}\cdot(V_a-0.4)^2\right]\cdot p^{0.144}\right\}}$ (9)	V_a (0.4-18 m/s) p (1 – 1000 l/(m^2·s))

$$corrI_t = 0.54 \cdot e^{(-0.15\cdot V_a)} \cdot p^{0.075} - 0.06 \cdot \ln(p) + 0.5 \quad (10)$$

Equation (10).

Table 1 presents the air velocity and relative humidity requirements for the testing of clothing thermal insulation.

EN ISO 15831 [1] and EN 342 [2] describe the same tests conditions. but EN ISO 9920 [3] gives preference to lower air velocity.

Wind effect on thermal insulation – correction equations

The influence of air velocity (V_a) on the thermal insulation was also the subject of EN ISO 9920 [3]. The standard [3] uses equations for the correction of thermal insulation values obtained for $V_a < 0.2$ m/s. These equations have a different form depending on the range of clothing thermal insulations. The corrective equations (without the influence of walking) are shown in ***Table 2***.

The wind effect (air velocity) on the thermal insulation of clothing has been the subject of research among many scientists. This topic has also been dealt with by Havenith and Nilsson [12-13]. They examined the influence of air velocity on the thermal insulation for clothing whose thermal insulation (calculated by the parallel method) ranged from 1.22 clo to 1.84 clo. The wind speed was in the range 0.15- 4.0 m/s. with a reference value of 0.15 m/s. For these data, a correction equation was created, which looked the same as ***Equation (7)***.

Nilsson et al. [14] also tested the wind effect for clothing whose thermal insulation ranged from 2.2 clo to 4.6 clo, but for air velocity in the range 0.4-18 m/s. In this case, the reference value was 0.4 m/s. According to Nilsson et al. [14], the correction equation for cold-weather clothing (I_t > 2.0 clo) is a function of the air permeability (p), wind speed (V_a) and walking speed (w). In our considerations, the walking speed is equal to 0, and the correction equation can be calculated by ***Equation (10)***.

Typical permeability values can be used: 1 l/(m^2s) for garments with impermeable membranes, 50 for densely woven workwear, and 1000 for highly permeable garments [12]. Nilsson et al. [14] tested the wind effect for air velocity in the range 0.4-18 m/s and noticed that air permeability for a wind speed below 2 m/s, has little influence on the thermal insulation. After re-analysis of the data by Havenith and Nilsson [12] the correction equation looked the same as ***Equation (9)***. For the lower area of the wind range (< 1.0 m/s), they suggested using ***Equation (8)***.

Also Lu et al. [15] tested the influence of wind speed on 17 sets of clothing ensembles. They tested three levels of wind speed: 0.15 m/s (namely no wind), 1.55 m/s and 4.0 m/s. The clothes were divided into three groups depending on their thermal insulation values. Group 1 was defined by It in the range 0.9-1.5 clo,

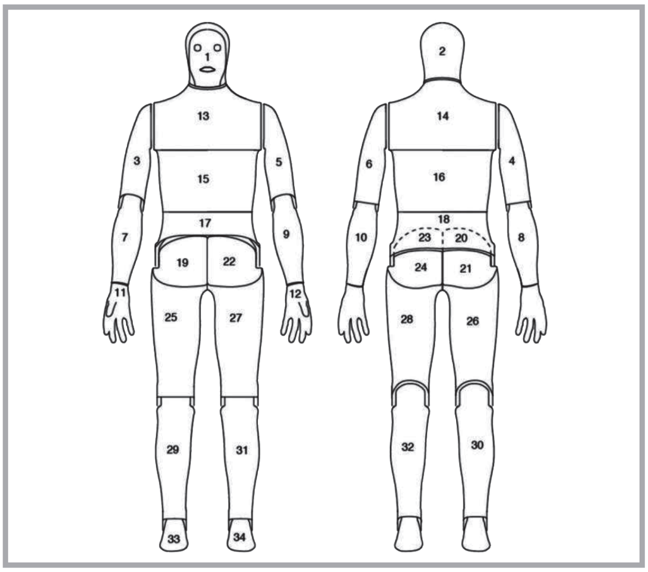

Figure 1. *Thermal manikin NEWTON divided into segments.*

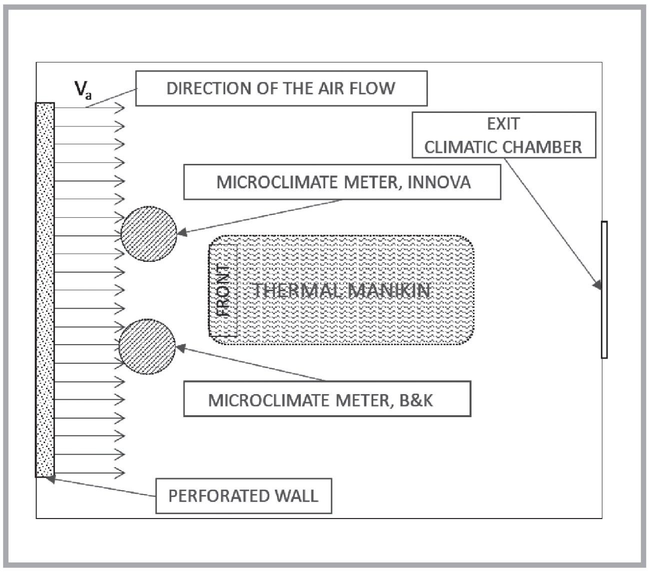

Figure 2. *Scheme of the research in a climatic chamber using a thermal manikin.*

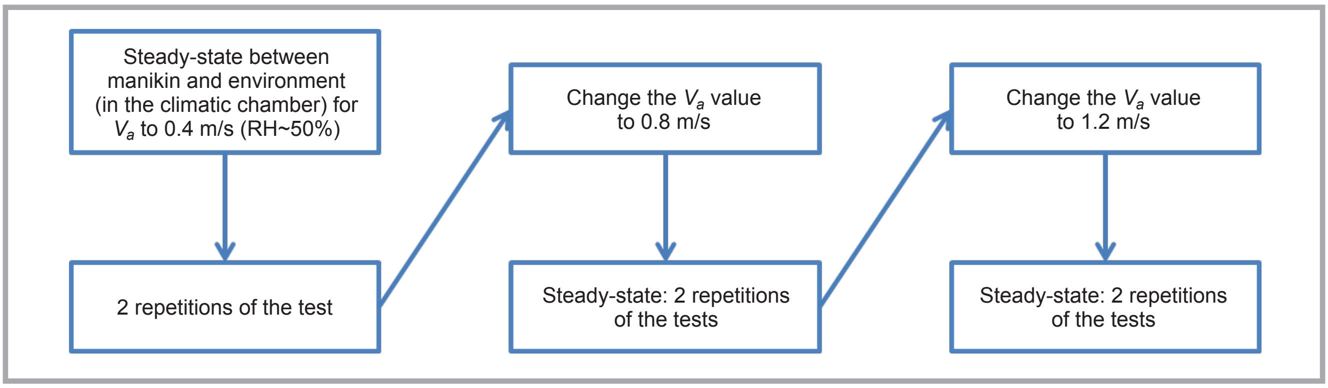

Figure 3. *Scheme for air velocity impact test of the thermal insulation.*

Figure 4. *Thermal manikin dressed in special skin.*

Figure 5. *Clothing tested (from left): baker' clothing and firefighter special clothing.*

group 2 in the range 1.5-2.3 clo and group 3 for a value higher than 3.2 clo. They also analysed three levels of walking speed. Based on those observations, they found a linear relationship with the static thermal insulation.

In the above-mentioned studies, mainly cold-protection clothes were tested (with a high value of thermal insulation). The tests were done with a large range of air velocity. The influence of low wind speed on clothing with a thermal insulation below 2 clo, was interesting to test. This research was carried out for 3 ensembles (for thermal insulation 0.7-1.6 clo) differing, inter alia, in the number of layers of material. The influence of air velocity on clothing thermal insulation was examined with three values of V_a. Due to the technical restraints of the climatic chamber, it was not possible to maintain a constant air velocity < 0.3 m/s during the test. For this reason, it was decided that the impact of air velocity V_a set at 0.4 m/s, 0.8 m/s and 1.2 m/s, respectively, would be examined. The correction factors (*CFs*) were calculated and compared with the *CF* values set out in EN ISO 9920 [3].

Table 3. *Summary of fabrics used in clothing tested.*

Layer\fabric	EN_1_skin	EN_2_BW	EN_3_FF
application	special skin fabric	Baker's clothing	special clothing for firefighter
1st layer	80% polyamide 20% elastine	80% polyamide 20% elastine	80% polyamide 20% elastine
2nd layer	–	65% polyestre 35% cotton (210 g/m^2)	outer fabric: 64% meta-aramide 35% para-aramide 1% anti-static fibres
3th layer	–	–	membrane: 65% para-aramide 35% polyurethane
4th layer	–	–	thermal barrier: aramide, FR fibres; integrated lining: 50% aramid fibre, 50% viscose

Material and methods

Test apparatus

Thermal manikin Newton. The thermal manikin Newton is a male body shape consisting of 34 segments (***Figure 1***) (Measurement Technology Northwest, USA).

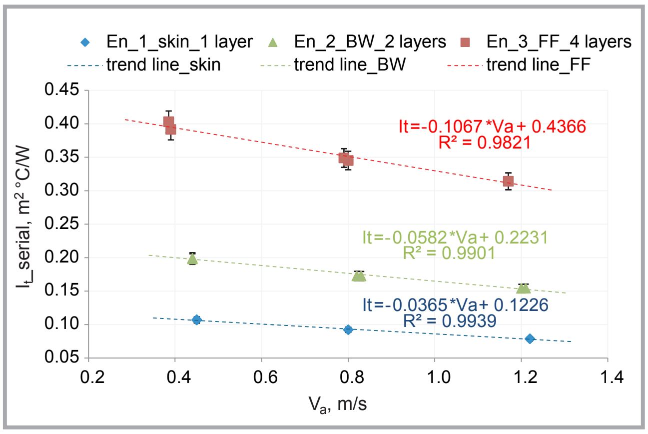

Figure 6. Dependences of the total thermal insulation value (I_t; serial method) on air velocity (V_a) for 50% relative humidity (with 4% permitted error).

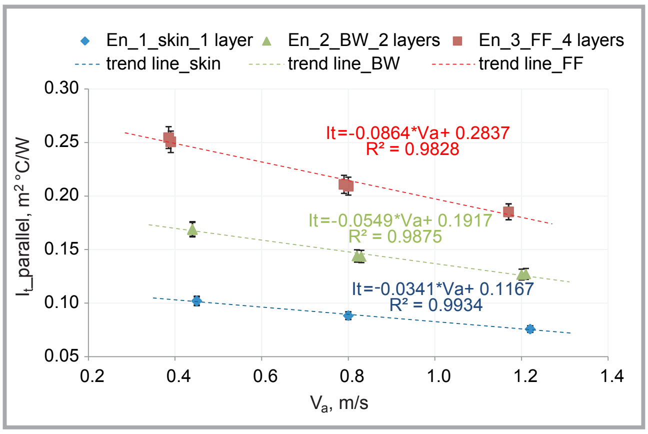

Figure 7. Dependences of the total thermal insulation value (I_t; parallel method) on air velocity (V_a) for 50% relative humidity (with 4% permitted error).

Climatic chamber. Air temperature in the climate chamber (Weiss) can be simulated from -40 °C to +70 °C. The construction of the chamber allows control of values such as: air velocity and relative humidity.The air velocity was carried out in a horizontal flow. The air flows through the perforated wall to the front of the thermal manikin.

Microclimate meters. Two microclimate meters controlled climate parameters: an Indoor Climate Analyser, from B&K, and an INNOVA. The uncertainty of measuring air velocity, air temperature and relative humidity was 0.05 m/s, 0.1 °C and 1%, respectively. An illustrative drawing of the research conducted in the climatic chamber is shown in ***Figure 2***.

Methodology

The impact of air velocity on dry heat exchange was examined with a thermal manikin (Newton) in a climate chamber. In order to check the influence of air velocity (V_a) for a constant value of relative humidity (RH 50%), 3 measurement points V_a were applied, i.e.: ~ 0.4 m/s, ~ 0.8 m/s and ~ 1.2 m/s.

The tests were performed according to the scheme shown in ***Figure 3***.

Clothing tested

The thermal manikin dressed in a special skin fabric was used to study the influence of air velocity on the thermal insulation (***Figure 4***).

Table 4. Slope coefficients of the mathematical relationship for the clothing tested.

	Serial		Parallel	
	"a"	"b"	"a"	"b"
EN_1 (1_layer)	-0.037	0.123	-0.034	0.117
EN_2 (2_layers)	-0.058	0.223	-0.055	0.192
EN_3 (4_layers)	-0.107	0.437	-0.086	0.284

Table 5. Thermal insulation testing conditions with standard deviations.

Ensemble	V_a ± 0.01, m/s	test 1		test 2	
		t_a ± 0.01, °C	RH ± 1, %	t_a ± 0.01, °C	RH ± 1, %
EN_1	0.45	20.4	50	20.4	50
	0.80	20.3	52	20.3	53
	1.22	20.3	53	20.3	53
EN_2	0.44	18.3	50	18.4	50
	0.83	18.3	51	18.3	50
	1.21	18.3	52	18.3	51
EN_3	0.39	12.3	51	12.3	48
	0.80	12.3	52	12.2	50
	1.17	12.2	51	12.2	50

The special skin fabric is made of polyamide and elastin. This material adheres closely to the heated surface of the manikin, thus preventing the creation of a so-called air space that could affect the total thermal insulation.

Two sets of clothing: for: a baker (BW) and firefighter (FF) were selected for further examination (***Figure 5***).

The skin fabric was close to the measuring surface. The baker's clothing (BW) was a single-layer ensemble and the special clothing for firefighters (FF) was a multi-layer ensemble. The materials used for the testing are summarised in ***Table 3***.

Results

Thermal insulation

The total thermal insulation (measured by the serial and parallel method) for different air velocities (0.4-0.8-1.2 m/s) and relative humidity ~ 50% in the climate chamber is shown in ***Figures 6-7***.

Values of the total thermal insulation I_t, calculated by the serial and parallel method were as follows, respectively: for the skin fabric – 0.11 m^2 °C/W (0.7 clo), for the baker's clothing – 0.20 m^2 °C/W (1.3 clo) and 0.17 m^2 °C/W (1.1 clo), and for the firefighter clothing – 0.40 m^2 °C/W (2.6 clo) and 0.25 m^2 °C/W (1.6 clo). The studies (***Figures 6-7***) showed that the air velocity affected the total thermal insulation, as calculated by the serial and parallel methods.

The study found that with air velocity V_a doubled from 0.4 m/s to 0.8 m/s, thermal insulation would drop by 13-14%, regardless of the number of layers in the clothing (for calculations made by the serial method). In the case of the parallel method, thermal insulation reductions were found to be in the range 14-17%.

With air velocity (V_a) tripled from 0.4 m/s to 1.2 m/s, thermal insulation dropped. For calculations made by the serial method, these values varied depending on the number of material layers. The largest decrease of 26% was recorded for 1-layer skin (EN_1), while for 2-layer and 4-layer clothing, the drop was in the range of 21-22%. For the parallel calculations, irrespective of the number of material layers, there was a decrease in thermal insulation of 25-27%.

The mathematical relationship $I_t = f(V_a)$ was calculated (***Figures 6-7***). The dependences obtained differed from each other in the slope coefficients of the straight line ("a"). The values are summarised in ***Table 4***.

The study found that the number of layers was directly proportional to the slope coefficients of the straight line. This effect of air velocity on the total thermal insulation of the clothing was found to be higher.

The mathematical relationship was calculated for air velocity in range from 0.4 m/s to 1.2 m/s. The coefficient "b" in that mathematical equation characterised the thermal insulation for air velocity equal to 0 m/s, but linearity was assumed in the range 0.4-1.2 m/s. This relationship cannot be extrapolated for air velocity below to 0.4 m/s.

Test conditions

Thermal insulation testing conditions for the manikin dressed in special skin (EN_1) for baker's clothing (EN_2) and special clothing for firefighters (EN_3) are shown in ***Table 5***. The air velocity during the test did not change by more than 0.01 m/s.

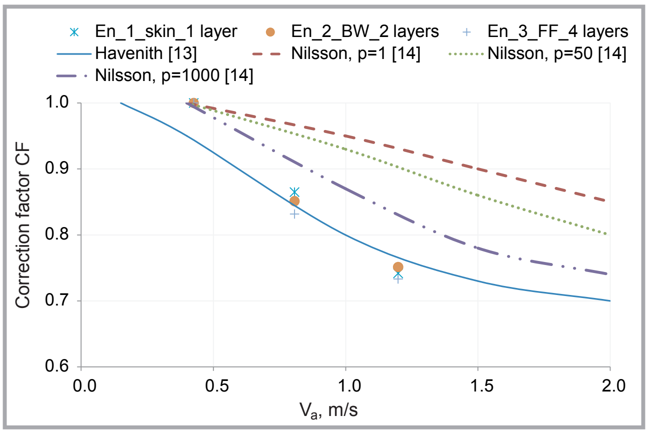

Figure 8. *Correction factor for conversion thermal insulation (parallel method) for all wind data; p – air permeability $l \cdot m^{-2} \cdot s^{-1}$ (according to [12]).*

Discussion

The wind effect on the thermal insulation in the range 1.2-3.5 clo was examined by scientists. Havenith and Nilsson [12-13], and Nilsson et al. [14] tested the influence wind speed with a reference value, 0.15 m/s and 0.4 m/s, respectively.

Based on their results, correction factors (*CFs*) were calculated to determine the changes in thermal insulation (I_{t_Va}) in relation to the base value obtained (I_{t_base}), according to the following ***Equation (11)***:

$$CF = \frac{I_{t\_Va}}{I_{t\_base}} \quad (11)$$

Air velocity was found to have a greater impact on higher thermal insulation values [12]. The correction factor values [12-14] for lower air velocity were compared with the results for the ensembles tested (***Figure 8***).

Figure 8 shows that the ensembles tested (thermal insulation (calculated by the parallel method)) in the range of 0.102-0.253 clo) for air velocity $V_a > 0.5$ m/s are best suited to the calculations made by Havenith and Nilsson [13], despite the differences in the reference value of the wind speed. ***Figure 8*** also shows that for lower air velocity values, the assumed linearity (as shown in ***Figures 6-7***) seems to be correct.

Based on ***Equation (7)*** (from ***Table 2***), the relationship between the correction factor (*CF*) and air velocity (V_a) was determined [3]. The dependence of CF obtained (corr I_t for 1.2 clo < I_t < 2.0 clo) was plotted on a common graph along with the CF calculated for the ensembles tested in the research variants (***Figures 9-10***).

According to EN ISO 9920 [3], the influence of air velocity depends on the air permeability of the outer layer and the type and number of openings in clothing. It has been shown that for many sets of clothing the wind effect is similar [3]. Similar conclusions were reached from

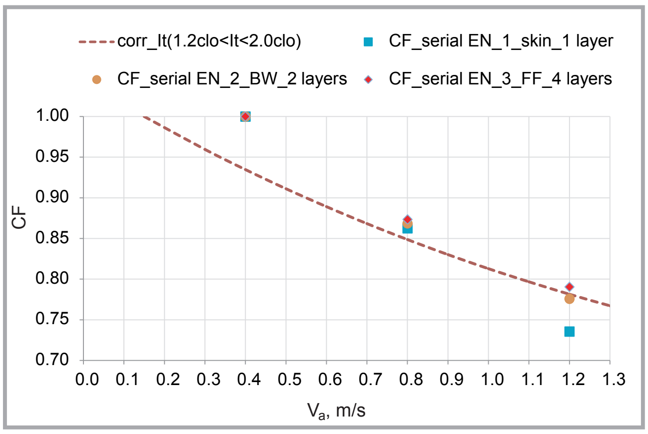

Figure 9. *Results of CF (corrIt for 1.2 clo < It < 2.0 clo) and CF calculated by the serial method for the variants tested.*

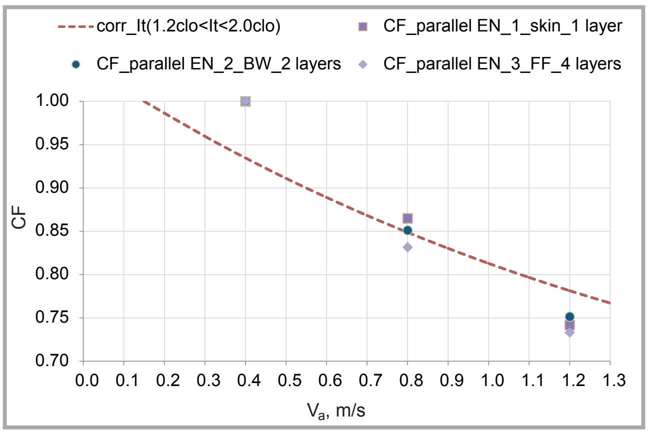

Figure 10. *Results of CF obtained (corrIt for 1.2 clo < It < 2.0 clo) and calculated (by parallel method) for the variants tested in the research.*

the research conducted. For the serial calculation method, similar CF values (0.86-0.87) were obtained for an air velocity of 0.8 m/s, regardless of the number of layers from which the clothing was constructed. However, for an air velocity of 1.2 m/s, the number of layers affected the CF value calculated. For single-layer skin, it was 0.74, while for two- and four-layer ensembles, the CF value was in range 0.78-0.79. In the parallel calculation method, similar values were obtained for EN_1 and EN_2 for an air velocity of 0.8 m/s and 1.2 m/s (0.86 and 0.75, respectively). Slightly lower CF values were recorded for EN_3, CF 0.83 and 0.73, respectively.

The results obtained were similar (for air velocity 0.8 m/s and 1.2 m/s) to the CF calculated according to EN ISO 9920 [3] (***Figures 9-10***).

Conclusions

The studies show a significant influence of air velocity on thermal insulation. For each of the sets of clothing examined (and specialised skin), mathematical relationships of the thermal parameters from the air velocity were recorded.

Theoretical considerations have shown that changes in air velocity above the range of 0.3-0.5 m/s, have a significant impact on the total thermal insulation. This dependence was also observed in a study using a thermal manikin [11-14]. The results obtained showed that in the case of clothing with thermal insulation ranging from 0.7 clo to 2.6 clo, doubling of the value of air velocity (from 0.4 m/s to 0.8 m/s) caused a reduction in thermal insulation, and that the number of layers did not affect it. For a higher value of air velocity (V_a 1.2 m/s), thermal insulation was found to decrease. For the serial method calculations, the percent reduction in thermal insulation depended on the number of layers of material. The largest decrease was recorded for single-layer skin, while for 2-layer and 4-layer clothing the drop observed was in the same range. There were no differences for the parallel calculations; irrespective of the number of material layers, where a decrease uin thermal insulation was observed in the same range. The results obtained were similar (for higher air velocity) to the CF calculated according to EN ISO 9920 [3].

A higher value of air velocity and number of layers in the clothing ensemble had a significant influence on the reduction in thermal insulation.

The main source of differences between the CFs calculated is the selection of the reference wind speed. The CFs calculated in cases where the wind speed changed, for example, to 0.7 m/s for a reference speed of 0.15 m/s or 0.4 m/s showed a different reduction in insulation. Having a reference wind speed of 0.4 m/s instead of 0.15 m/s will obtain lower correction factors for higher air speeds when the higher reference wind speed is used [12]. According to Havenith and Nilsson [12], a low reference wind speed is best for an ensemble with low thermal insulation (like clothes for office workers and most industrial workers). But for cold-weather clothing, a higher reference wind speed should be used. This reference value (0.4 m/s) is also found in the standards [1-2]. Havenith and Nilsson [12-13] and Nilsson et al. [14] for the ensembles tested (with the total thermal insulation above 1.2 clo) used a reference value equal to 0.15 m/s and 0.4 m/s, respectively. Lu et al. [15] also used 0.15 m/s as a reference value even when they tested clothes with very high thermal insulation (I_t > 3.2 clo).

However, it should be remembered that many chambers used for the measurements cannot run stably at very low air speeds. A higher value is easier to achieve and could be used for clothes with low thermal insulation. For which reference values the correction factors were calculated should be noted.

Acknowledgements

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