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Selection of Clothing for a Cold Environment by Predicting Thermophysiological Comfort Limits

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Abstract
Results are presented from a study on the prediction of the insulation abilities of outerwear clothing for cold protection from the point of view of the thermophysiological comfort of the wearer. The Required Clothing Insulation (IREQ) index is used to simulate the abilities of 14 assemblies of layers designed for the production of winter jackets to protect the body in different cold environments. The calculations allow to assess the limits of applicability of the garments in terms of the thermophysiological comfort assured, the activities performed and the weather conditions. Discussions are presented on the correspondence between ISO11079:2007 and the online JavaScript code for calculation of IREQ based on it. The results predicted and their analysis have a practical use, as they allow to estimate the cold protection effectiveness of the textile layers used in an assembly at the design stage, thus giving room for necessary changes depending on the conditions of its use.

Key words: *cold environment, thermophysiological comfort, IREQ index, design stage, prediction, insulation abilities.*

Introduction

Thermophysiological comfort is related to the maintenance of a balance between the heat generated by the human body, and the heat losses from the body to the environment. A low temperature environment poses a significant risk to the human body in terms of comfort, performance and health. Clothing items for cold protection should provide the necessary thermophysiological comfort by playing the role of a protective barrier between the body and the environment [1, 2].

In conditions of thermal neutrality and rest the temperature of the core body is around 37°C [3]. When this temperature drops below the normal value, the body begins to cool and sends signals to the hypothalamus gland in the brain. The hypothalamus forwards pulse signals to two other mechanisms for temperature regulation: vasoconstriction and shivering. The constriction of blood vessels reduces the blood flow in areas close to the skin, and body extremities, decreasing heat loss. Shivering provokes heat production by uncontrolled muscle work till the depletion of muscle glycogen [4].

Behavioral reactions are much more important for maintaining thermophysiological comfort in case of a cold environment than in others (moderate or hot environment). The proper selection of clothing items and decrement of the skin surface area that is in direct contact with the environment are of crucial importance for the protection of the human body and for decreasing cold stress [5]. It is therefore very logical that the International Standard ISO 11079 [6] deals with the determination and interpretation of cold stress by means of the Required Clothing Insulation (IREQ) index.

The IREQ index was proposed in a mathematical model for assessment of cold stress [7, 8], included later in an ISO Technical Report [9] and International Standard ISO 11079 [6]. The model integrated the effect of environmental factors (air temperature, air velocity, relative humidity, mean radiant temperature) and personal factors (clothing insulation and metabolic activity) on human thermophysiological comfort in a cold environment.

The IREQ index can be used for solving different practical problems:
- to assess the preservation of heat balance in a low temperature environment;
- to help the selection of appropriate clothing for different combinations of "environmental conditions – activity";
- to design and manage the activities in a cold environment, etc.

Different authors have used the IREQ index in their research works. It was applied to assess cold stress in a low temperature environment [10], including local cooling [11]. Griefahn [12] used the IREQ index to evaluate the thermal insulation of garments worn in real working conditions of a moderate cold environment and the appropriateness of the index for use in temperatures above 10°C. The IREQ index was applied to assess different occupational cold environments and the clothing insulation used by workers [13-15], including an extremely cold environment [16]. It was also used to study the effect of wind on the insulation abilities of military clothing [17].

The aim of the present study was to predict the insulation abilities of 14 assemblies of layers designed for the production of winter jackets based on a mathematical model for calculation of the IREQ index. The predictions allow to assess the limits of applicability of the garments from the point of view of the thermophysiological comfort of the wearer, the activities performed and the weather conditions. The results obtained have a practical use, as they allow to assess the cold protection effectiveness of the textile layers used in an assembly at the design stage and to be changed, if necessary, so that the clothing item obtains higher or lower insulation abilities depending on the conditions of its use.

Comments on ISO 11079:2007 and its online code for IREQ index calculation

Applicability of the IREQ index to assess thermophysiological comfort limits

A state of thermophysiological comfort is reached when the body is relaxed and its sensors for "warmth" and "cold" are not activated, i.e. the body is in thermal neutrality. One of the interpretations of the IREQ index is to assess physiological strain in a cold environment, defined as the change in body temperature, skin wetness and the mean skin temperature. The IREQ index is determined as:

$$\mathrm{IREQ} = \frac{\bar{t}_{sk} - t_{cl}}{R + C}, \text{ clo} \qquad (1)$$

where, $\bar{t}_{sk}$ is the mean skin temperature, °C, t_{cl} the clothing surface temperature, °C, R the radiative heat exchange, W/m^2, and C is the convective heat exchange, W/m^2.

Equation (1) has to be iteratively solved together with the heat-balance equation for the human body [18]:

$$M - W = E_{res} + C_{res} + K + C + R + E + S \qquad (2)$$

where, M is the metabolic rate, W/m^2, W the effective mechanical power, W/m^2, E_{res} heat losses due to respiration, W/m^2, C_{res} respiratory convective heat losses, W/m^2, K heat losses due to conduction, W/m^2, E heat losses due to evaporation, W/m^2, and S is the body heat storage rate, W/m^2.

Equation (2) can be simplified assuming steady state conditions (S = 0) and negligible heat losses due to conduction (K = 0) [19].

Two levels of the IREQ index are defined [6]:

- $\mathrm{IREQ}_{neutral}$: this is the thermal insulation of clothing that keeps the body in a state of thermophysiological comfort.
- IREQ_{min}: this is the minimal thermal insulation of the garment which can maintain the body's thermal equilibrium at a lower than required by the mean body temperature. This means that the constant cooling of the body appears, and the exposure to the cold environment has to be limited.

The algorithm for application of the value of the required clothing insulation predicted (namely the IREQ index) includes a preliminary assessment of the thermal insulation of clothing Icl,r, whose use is anticipated. The value of $I_{cl,r}$, is adjusted to the resultant insulation value $I_{a,r}$, and then is compared with the value of IREQ index calculated. The comparison makes it possible to assess the thermal balance expected during specific conditions (environmental and personal). It includes the following scenarios:

- *Scenario 1*: If the corrected value for the thermal insulation of the garment is greater than the neutral value of the IREQ ($I_{cl,r} > IREQ_{neutral}$), the thermal insulation of the garment must be reduced to avoid overheating, especially when activity is high.
- *Scenario 2*: If the corrected value for the thermal insulation of the garment is between the two values of the IREQ index ($IREQ_{\min} \le I_{cl,r} \le IREQ_{neutral}$), the heat balance between the body heat generated and heat losses to the cold environment can be maintained for a certain period of time. The closer to the $IREQ_{neutral}$ the thermal insulation of the real clothing is, the closer to the state of thermophysiological comfort the body is.
- *Scenario* 3: If the corrected value for the thermal insulation of the clothing is less than the minimal value of the IREQ index ($I_{cl,r} < IREQ_{\min}$), the body is beyond the limits of thermophysiological comfort and exposed to the risk of cold injuries. This requires to increase the thermal insulation of the garment to prevent the progressive cooling of the body or to stop the exposure.

Scenarios 2 and 3 require the period of exposure to a cold environment to be limited; thus ISO 11097 [6] recommends calculation of the duration of the limited exposure (DLE index), namely:

$$\mathrm{DLE} = \frac{Q_{\lim}}{S} \qquad (3)$$

where, $Q_{\lim}$ is the limit value of body heat gain or loss, kJ/m^2.

Difficulties in the use of the online JavaScript code

ISO 11079:2007 [6] provides a mathematical model for simulation of the IREQ index and DLE (written in the standard as "$D_{\lim}$"), together with a computer program – a JavaScript code, which can be used online or downloaded for use on a personal computer [20]. Our experience with the online program for simulation has shown some instability of the software, related to the prediction of different values for the IREQ index and DLE index when one and the same initial values are imported. However, the most important restrictions are related to the incorporated limits of some of the values, which do not allow to use the online software for temperatures above 10°C or for air flow velocity below 0.4 m/s. It should be mentioned that the study by Griefahn [12] found the applicability of the IREQ index for environments with a temperature of up to 15°C. At the same time the air velocity in some work places in an artificial cold environment or during measurements in climatic chambers can be less than 0.4 m/s. Restrictions are also incorporated in the online program concerning the input value of the clothing insulation available.

Conformity between ISO 11079:2007 and the JavaScript code based on it

On the basis of the mathematical model presented in [6] we developed a code, written in the Pascal programming language, to simulate the IREQ index and DLE index. Writing the program, we ascertained that the need for calculation equations was not presented in the mathematical model in [6]. Debugging the program and trying to compare the results obtained with the predictions of the online program, we found out that the JavaScript code [20] has some inconsistences with [6]. Our remarks can be summarised as follows:

1) The equation for calculating the saturated water vapor pressure at the expired air temperature p_{ex} is missing in the mathematical model proposed in [6]. The same is valid for the formula for the water vapor partial pressure p_a. In our program we used the respective equations from [18].
2) ***Equation (4)*** for the saturated water vapor pressure at the skin surface $p_{sk,s}$ included in the mathematical model in [6] is based on the mean skin temperature t_{sk} (although in equation in [6] the symbol for the local skin temperature is written):

$$p_{sk,s} = 610,78.e^{\frac{17,27.t_{sk}}{t_{sk}+23,3}}, \text{ kPa} \qquad (4)$$

Instead of ***Equation (4)***, ***Equation (5)*** is used in the JavaScript code [20], taken from [9]:

$$p_{sk,s} = 0,1333.e^{\frac{18,6686-4030,183}{t_{sk}+235}} \quad (5)$$

3) ***Equation (6)*** for calculation of the total evaporative resistance of the clothing and boundary air layer $R_{e,T}$ is written in [6] as

$$R_{e,T} = 0,16.(\frac{I_{a,r}}{f_{cl}} + I_{cl,r}) \quad (6)$$

where $I_{a,r}$ is the resultant boundary layer thermal insulation, m^2KW^{-1}; f_{cl} the dimensionless clothing area factor, and $I_{cl,r}$ is the resultant clothing insulation, m^2KW^{-1}.

In the online code, ***Equation (7)*** is used instead [20]:

$$R_{e,T} = 0,16.(I_{a,r} + I_{cl,r}) \quad (7)$$

4) ***Equation (8)*** is proposed in [6] for determination of the radiative heat transfer coefficient h_r, namely:

$$h_r \approx \sigma.\varepsilon_{cl}.\frac{(t_{cl}+273)^4 - (t_r+273)^4}{t_{cl}-t_r}, \quad W.m^{-2}.K \quad (8)$$

where, σ = (5,67.10^{-8}) $Wm^{-2}K^{-4}$ is the Stefan-Boltzmann constant, ε_{cl} the dimensionless clothing emissivity surface, which depends on the temperature of the radiation source, t_{cl} the clothing surface temperature, °C, and t_r is the radiant temperature, °C (often similar to the air temperature).

In the JavaScript code, ***Equation (9)*** is used instead of ***Equation (8)***, namely [20]:

$$h_r = 5,67.10^{-8}.0,95.\frac{Ar}{Adu}.\frac{e^{4.\log(273+T_{cl})} - e^{4\log(273+T_r)}}{T_{cl}-T_r}, \quad (9)$$

where Ar is the body surface area taking part in the radiation heat exchange, m^2, Adu the Dubois body surface area, m^2. T_{cl} the clothing surface temperature, °C and T_r is the radiant temperature, °C.

Equation (9) is neither included in [6] nor in [9], where ***Equation (10)*** is used instead of ***Equation (8)***:

$$h_r = 5,67.10^{-8}.0,97.\frac{Ar}{Adu}.\frac{e^{4.\ln(273+T_{cl})} - e^{4\ln(273+T_r)}}{T_{cl}-T_r}. \quad (10)$$

A discrepancy can be found in the term Ar/Adu, the use of a decimal logarithm instead of a natural logarithm (because $e^{\ln(x)} = x$), and the different value of the clothing emissivity surface ε_{cl} (0.97 in [6] and 0.95 in [20]).

5) The convective heat transfer coefficient h_c is determined in [6] according to ***Equation (11)***:

$$h_c = \frac{f_{cl}}{I_{a,r}} - h_r, W.m^{-2}.K \quad (11)$$

In the online JavaScript code [20], ***Equation (12)*** is used, taken from ISO9920 [21]:

$$h_c = \frac{1}{I_a - h_r} \quad (12)$$

6) ***Equation 10*** for calculation of the clothing factor f_{cl} is written in [6] as

$$f_{cl} = 1 + 1.97\ I_{cl} \quad (13)$$

while in the online code [20] the following equation is used:

$$f_{cl} = 1 + 1.197\ I_{cl} \quad (14)$$

It has to be mentioned that the work of d'Ambrosio Alfano et al. [19] presents a comprehensive analysis of [6]. The authors criticise different aspects of the standard and it is possible for some of the corrections in [20] to be inserted later on on the basis of the suggestions made in [19]. However, it is difficult for a regular reader who follows the mathematical model in [6] to recognise the reasons for the discrepancies in the online program [20] based on the standard [6].

Materials and methods

The IREQ index was applied to predict the insulation abilities of 14 ensembles of layers designed for the production of winter jackets. Each system consisted of an outer layer (woven fabric), a hidden insulating layer (nonwoven polyester web), and a lining (woven fabric). The thermal insulation of the ensembles was determined on the basis of their thermal resistance, measured according to EN ISO 11092 [22] with Permatest apparatus. ***Table 1*** includes a description of the layers in each ensemble and data for their thermal insulation.

For calculation of the IREQ index, a clothing ensamble was added to the

Table 1. *Description of the ensembles and thermal insulation data.*

Sample	Upper layer	Middle layer	Lining	Thickness of ensemble, mm	Thermal insulation, clo	
					Jacket	Total
1	PES100%	PES100%	PES100%	13.47	1.38	2.28
2	PA/PU 90/10%	PES100%	PES100%	13.12	0.87	1.77
3	CO100%	PES100%	CO100%	14.41	0.99	1.89
4	PA100%	PES100%	PES100%	13.06	1.02	1.92
5	PA100%	PES100%	PES100%	13.20	0.94	1.84
6	PES100%	PES100%	PES100%	13.17	1.05	1.95
7	PES100%	PES100%	PES100%	13.13	1.07	1.97
8	PES100%	PES100%	PES100%	10.23	0.92	1.82
9	PA/PU 90/10%	PES100%	PES100%	9.88	0.63	1.53
10	CO100%	PES100%	CO100%	11.17	0.73	1.63
11	PA100%	PES100%	PES100%	9.82	0.65	1.55
12	PA100%	PES100%	PES100%	9.96	0.74	1.64
13	PES100%	PES100%	PES100%	9.93	0.75	1.65
14	PES100%	PES100%	PES100%	9.88	0.76	1.66

Table 2. *Predicted IREQ index*

Case	Conditions	Air Temperature °C	15	10	5	0	-5	-10	-15	-20	-25	-30
1	Activity 80 W/m^2 Air velocity 0.14 m/s	$IREQ_{neutral}$ clo	1.55	2.07	2.58	3.07	3.56	4.05	4.54	5.04	5.51	5.98
		$IREQ_{min}$ clo	1.19	1.71	2.21	2.71	3.2	3.69	4.18	4.67	5.15	5.64
2	Activity 134 W/m^2 Air velocity 0.14 m/s	$IREQ_{neutral}$ clo	0.7	1.04	1.37	1.68	1.99	2.29	2.59	2.89	3.19	3.49
		$IREQ_{min}$ clo	0.36	0.71	1.03	1.35	1.66	1.97	2.27	2.57	2.86	3.16
3	Activity 134 W/m^2 Air velocity 3 m/s	$IREQ_{neutral}$ clo	0.85	1.16	1.47	1.77	2.07	2.36	2.66	2.95	3.24	3.53
		$IREQ_{min}$ clo	0.54	0.85	1.15	1.45	1.75	2.04	2.33	2.63	2.92	3.21

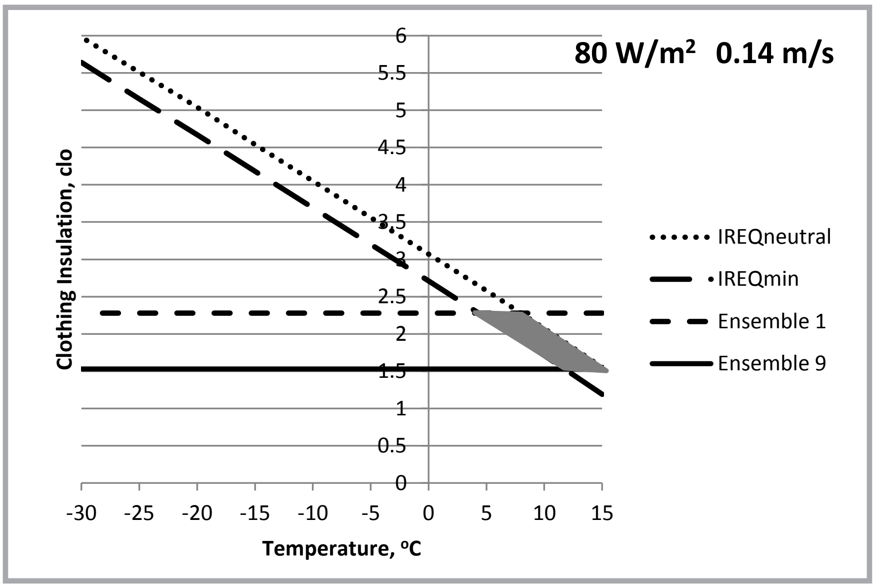

Figure 1. Thermophysiological limits ensured by the ensembles investigated: standing position or light sedentary work, calm environment (Case 1).

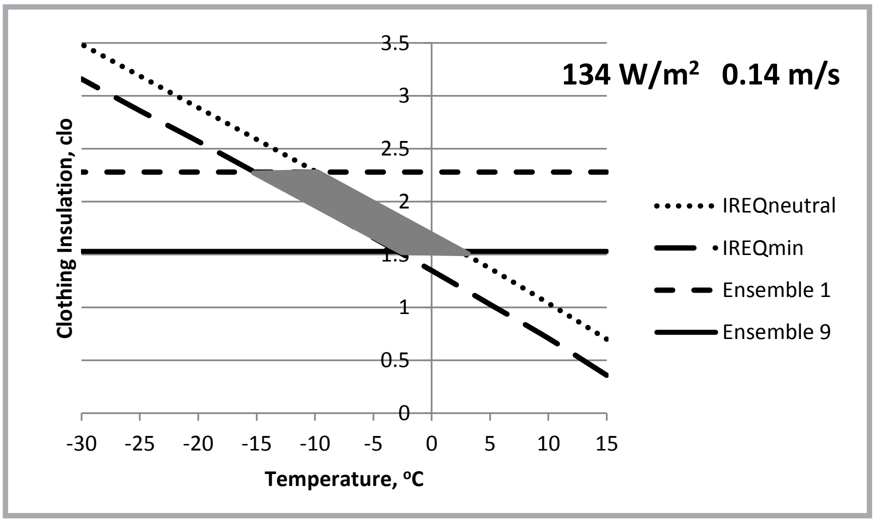

Figure 2. Thermophysiological limits, ensured by the ensembles investigated: slow walking, calm environment (Case 2).

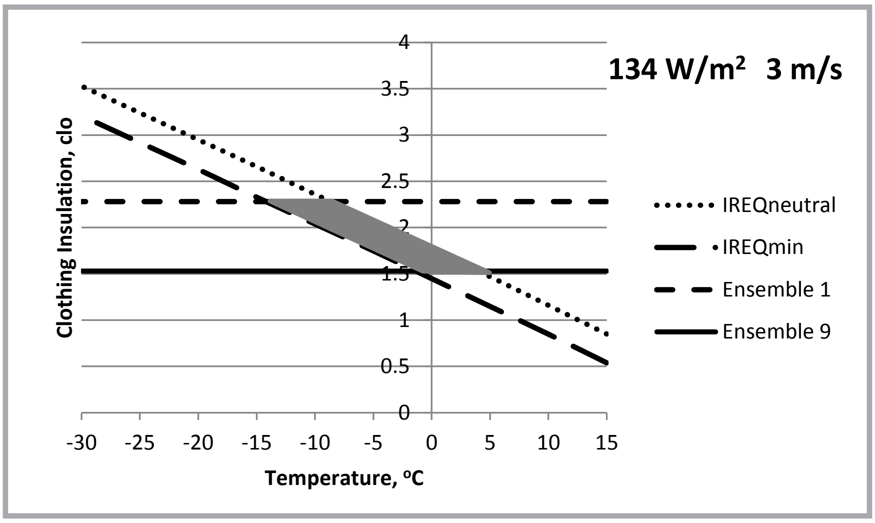

Figure 3. Thermophysiological limits, ensured by the ensembles investigated: slow walking, light breeze (Case 3).

winter jackets to obtain the total thermal insulation of the virtual clothed human body. The clothing ensamble included underwear (0.04 clo), socks (0.05 clo), ankle boots (0.02 clo), denim working trousers (0.15 clo), a long sleeve cotton shirt (0.25 clo), and a sweatshirt (0.39 clo) (data from measurements and [21]). The total value was 0.9 clo, added to the thermal insulation of the jackets.

Calculation of the IREQ index was done for a range of air temperatures: from +15 to -30°C, with a step of 5°C. The air humidity was set to a constant of 61% for all cases to assess the change in temperature only (measured during real experiments with humans in -11 deg C and 61% relative humidity, performed in a climatic chamber).Two metabolic rates were tested: 80 W/m^2 (standing position or light sedentary work in an artificial cold environment) and 134 W/m^2 (slow walking on a flat surface at a speed of 2.7 km/h). Two air velocities were also tested: 0.14 m/s (calm outdoor or artificial cold environment) and 3 m/s (light breeze, wind felt on exposed skin).

Results and discussions

The results from calculations of the two boundary values of the IREQ index (IREQ$_{min}$ and IREQ$_{neutral}$) for the cases studied are summarised in ***Table 2***.

Analysis of the predicted values showed that the most difficult was to achieve thermophysiological comfort of the body in Case 1 (standing or sitting posture at a metabolic rate of 80 W/m^2): the simulated conditions required the highest values of clothing insulation (IREQ$_{neutral}$) to be available so as to sustain the virtual body in thermophysiological comfort. The increment of the metabolic rate to 134 W/m^2 decreased the value of IREQ$_{neutral}$, which meant that the clothing ensemble with less insulation was enough to protect the body in thermal neutrality. The augmentation of the air velocity to 3 m/s decreased the results for IREQ$_{neutral}$ slightly in comparison with the calm environment.

Figures 1-3 combine the results for IREQ$_{neutral}$ and IREQ$_{min}$ for Cases 1-3, respectively, together with the range of clothing insulation of the ensembles studied, enclosed between Ensemble 1 (with the highest clothing insulation of 2.28 clo) and Ensemble 9 (with the lowest clothing insulation of 1.53 clo).

The graph in ***Figure 1*** shows that below the line of $IREQ_{neutral}$ the body leaves the state of thermophysiological comfort. A constant cooling appears, but the cold strain is still bearable for the thermoregulatory system of the body – till the line of $IREQ_{min}$. Below the line of $IREQ_{min}$ the body is in a danger from cold injuries. At the same time the two lines of the clothing insulation of Ensembles 1 and 9 clearly show the ability of the available clothing ensembles to ensure the thermophysiological comfort of the body. The outlined shape between the four lines presents the temperature interval where the available clothing insulation can protect the body. The main inference here is that none of the 14 ensembles will ensure the thermophysiological comfort of the body in subzero conditions if the metabolic activity is up to 80 W/m^2.

Figure 2 presents the results for increased activity in a calm environment: the thermophysiological comfort is ensured in a subzero environment (up to -5°C) by the most insulated jackets (Ensembles 4, 6 and 7). Ensemble 1 keeps the body in thermophysiological comfort up to -10°C. The ensembles with the lowest values of thermal insulation (Ensembles 9-14) assure thermophysiological comfort at temperatures above 0°C, but can be used for a limited time at temperatures up to -5°C. The most insulated jackets can be used for a limited time in the temperature range from -5°C to -15°C.

Figure 3 shows that the increment of the air velocity to 3 m/s replaces the thermophysiological limits ensured by the ensembles investigated at higher temperatures. Certainly this is related to the wind-chill effect, which is estimated by the IREQ index model. It can be concluded that only the ensembles with clothing insulation of 1.77 clo or higher will maintain the body in thermophysiological comfort at 0°C (Ensembles 1-7). They can be used at lower temperatures up to -10°C or up to -15°C (only Ensemble 1) for a limited time; but the body will be in constant cooling.

The duration of limited exposure in a cold environment (DLE index) was also predicted for each of the cases. ***Table 3*** summarises the results for Case 1, which is the worst case for the achievement of thermophysiological comfort from the three cases investigated. Two levels of the DLE index were calculated [20]:

- $DLE_{neutral}$, which corresponds to $IREQ_{neutral}$; this value is lower than the DLE_{min};
- DLE_{min}, which corresponds to $IREQ_{min}$; the exposure of the body in a cold environment has to stop after the predicted value of DLE_{min}.

The results for the DLE index may be presented graphically and different analysis can be performed.

Figure 4 (see page 100) presents the results for the $DLE_{neutral}$ for Ensembles 1 and 9, which have the highest and lowest clothing insulation: 2.28 clo and 1.53 clo, respectively. The graphs show the time of cold exposure in which the body will be in a state of thermophysiological comfort. The limit of 8 hours or more (one working shift, for example) is reached by Ensemble 1 in an environment with a temperature of 5°C or more, while Ensemble 9 can protect the body in thermophysiological comfort for 8 hours at 15°C only. With the decrement of the temperature, the abilities of the two ensembles to maintain the body's thermophysiological comfort are akin to each other; the value of $DLE_{neutral}$ for Ensemble 1 is almost twice that of $DLE_{neutral}$ for Ensemble 9, however.

The results from the prediction of DLE_{min} for Ensembles 1 and 9 are presented in ***Figure 5*** (see page 100). The two graphs show the maximum exposure of the body in conditions of constant cooling. The exposure for each of the ensembles cannot be prolonged below the limit outlined by the graph for the respective insulating value.

Figures 6 and ***7*** (see page 101) show a comparison between $DLE_{neutral}$ and DLE_{min} for all ensembles studied, for three peculiar air temperatures: 0°C, -15°C and -30°C. The vertical axis of the two figures is one and the same to allow easier visual comparison between the results.

Having constant clothing items and different jackets in each ensemble, it is obvious that the insulation abilities of the jackets make a difference to the values of $DLE_{neutral}$ and DLE_{min}. Ensembles 1-8 can assure thermophysiological comfort of the body at 0°C for 1 to 1.5 hours and Ensemble 1 can do so for slightly more than 2 hours. The rest of the ensembles

Table 3. *Predicted duration of limited exposure.*

Ensemble	Air temperature °C	15	10	5	0	-5	-10	-15	-20	-25	-30
Ensemble 1 2.28 clo	$DLE_{neutral}$, h	8	8	8	2.23	1.27	0.89	0.68	0.55	0.47	0.4
	DLE_{min}, h	8	8	8	4.05	1.7	1.08	0.79	0.62	0.51	0.44
Ensemble 2 1.77 clo	$DLE_{neutral}$, h	8	7.74	1.83	1.03	0.72	0.55	0.45	0.38	0.33	0.29
	DLE_{min}, h	8	8	3.25	1.37	0.88	0.64	0.51	0.42	0.36	0.31
Ensemble 3 1.89 clo	$DLE_{neutral}$, h	8	8	2.13	1.21	0.81	0.62	0.5	0.41	0.36	0.31
	DLE_{min}, h	8	8	5.13	1.68	1.01	0.72	0.56	0.46	0.39	0.34
Ensemble 4 1.92 clo	$DLE_{neutral}$, h	8	8	2.49	1.26	0.84	0.63	0.51	0.42	0.36	0.32
	DLE_{min}, h	8	8	6.03	1.77	1.05	0.73	0.58	0.47	0.4	0.34
Ensemble 5 1.84 clo	$DLE_{neutral}$, h	8	8	2.09	1.13	0.77	0.59	0.48	0.4	0.34	0.3
	DLE_{min}, h	8	8	4.14	1.54	0.95	0.69	0.54	0.44	0.38	0.33
Ensemble 6 1.95 clo	$DLE_{neutral}$, h	8	8	2.68	1.28	0.87	0.65	0.52	0.43	0.37	0.33
	DLE_{min}, h	8	8	6.9	1.87	1.08	0.76	0.59	0.48	0.41	0.35
Ensemble 7 1.97 clo	$DLE_{neutral}$, h	8	8	2.83	1.35	0.89	0.66	0.53	0.44	0.38	0.33
	DLE_{min}, h	8	8	7.6	1.94	1.11	0.78	0.6	0.49	0.41	0.36
Ensemble 8 1.82 clo	$DLE_{neutral}$, h	8	8	2	1.1	0.76	0.58	0.47	0.39	0.34	0.3
	DLE_{min}, h	8	8	3.94	1.5	0.93	0.67	0.53	0.43	0.37	0.32
Ensemble 9 1.53 clo	$DLE_{neutral}$, h	8	2.74	1.2	0.77	0.56	0.45	0.37	0.32	0.27	0.24
	DLE_{min}, h	8	8	1.79	0.97	0.67	0.51	0.41	0.35	0.3	0.26
Ensemble 10 1.63 clo	$DLE_{neutral}$, h	8	3.83	1.41	0.86	0.62	0.45	0.4	0.34	0.3	0.26
	DLE_{min}, h	8	8	2.23	1.12	0.75	0.51	0.45	0.38	0.32	0.28
Ensemble 11 1.55 clo	$DLE_{neutral}$, h	8	2.91	1.24	0.78	0.58	0.45	0.38	0.32	0.28	0.25
	DLE_{min}, h	8	8	1.9	1	0.68	0.52	0.42	0.35	0.3	0.26
Ensemble 12 1.64 clo	$DLE_{neutral}$, h	8	4	1.44	0.88	0.63	0.53	0.4	0.34	0.3	0.26
	DLE_{min}, h	8	8	2.3	1.13	0.75	0.57	0.45	0.38	0.32	0.28
Ensemble 13 1.65 clo	$DLE_{neutral}$, h	8	4.16	1.45	0.89	0.64	0.5	0.41	0.35	0.3	0.27
	DLE_{min}, h	8	8	2.34	1.14	0.74	0.57	0.46	0.38	0.33	0.28
Ensemble 14 1.66 clo	$DLE_{neutral}$, h	8	4.34	1.48	0.89	0.64	0.5	0.41	0.35	0.3	0.27
	DLE_{min}, h	8	8	2.41	1.17	0.77	0.58	0.46	0.38	0.33	0.29

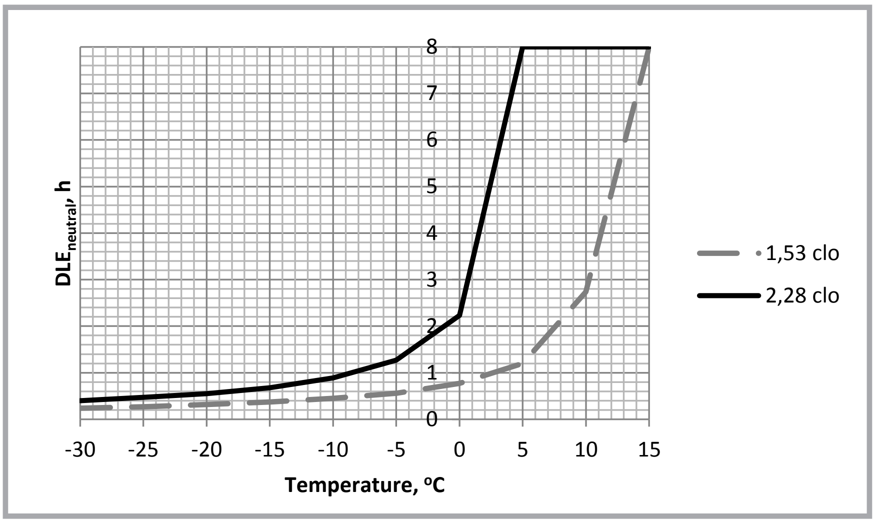

Figure 4. *Duration of exposure in conditions of thermophysiological comfort for Ensemble 1 and Ensemble 9.*

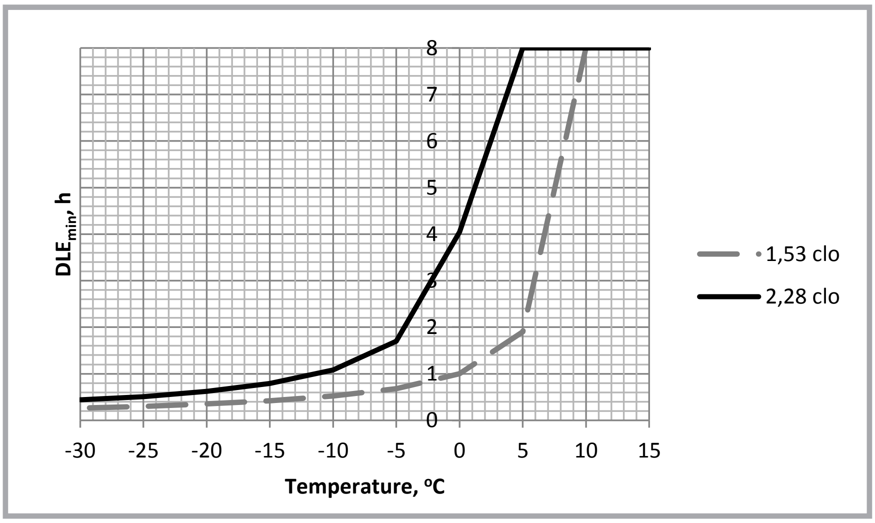

Figure 5. *Maximum exposure in conditions of constant cooling of the body for Ensemble 1 and Ensemble 9.*

are able to sustain the body in thermophysiological comfort at 0°C for less than an hour.

At -15°C the difference between the insulation abilities of the ensembles is much smaller: only Ensemble 1 can maintain thermophysiological comfort for more than 40 min, while all others do so from 32 (Ensemble 7) to 22 min (Ensemble 9). In an environment with the temperature of -30°C DLE$_{neutral}$ for all samples is below 20 min, except for Ensemble 1.

The predicted values of DLE$_{min}$ show the same tendencies, as in ***Figure 6***. Evidently the period of human exposure in ancold environment is prolonged as the body is beyond thermophysiological comfort in a state of constant cooling, which can still be bearable for the thermoregulatory system. Almost all ensembles allow simulated activity to be performed for 60 min (except Ensemble 9) at 0°C. Ensembles 3-9 can counterpoise the constant cooling of the body up to 90 min, and only Ensemble 1 – for more than 4 hours.

The decrement of the air temperature to -15°C limits the exposure from 36 min (with Ensemble 7) to 25 min (with Ensemble 9), and only for the exposure of a person dressed in jacket 1 (Ensemble 1) can it be up to 47 min. The simulated activity at a temperature of -30°C can continue for a period from 15 to 20 min, with longer periods being dangerous for the human body.

Conclusion

In this study results are presented from the prediction of the insulation abilities of 14 clothing items for cold protection from the point of view of thermophysiological comfort of the wearer. The Required Clothing Insulation (IREQ) index was used to simulate the abilities of 14 assemblies of layers designed for the production of winter jackets to protect the body in three types of cold environment with different levels of activity. An own code was developed for predictions of IREQ and DLE indexes based on the mathematical model presented in ISO11079:2007.

The results obtained showed that none of the 14 jackets will ensure thermophysiological comfort of the body in a standing or sitting posture in subzero conditions. If the person is active (slow walking) jackets 4, 6 and 7 will ensure thermophysiological comfort up to -5°C, and jacket 1 – up to -10°C. The jackets with the lowest insulation values (jackets 9-14) will ensure thermophysiological comfort at temperatures above 0°C, but can be used for a limited time at temperatures up to -5°C. The most insulated jackets (jackets 1-8) can be used for a limited time at temperatures from -5°C to -15°C.

Calculation of the DLE index allowed to estimate the time of exposure of a person, wearing the 14 jackets in different environmental conditions and activity. It was found that at a temperature of 0°C or lower none of the jackets would protect the body for periods longer than 2 hours if the person is moving slowly. Three options are possible: to increase the insulation abilities of the layers, anticipated for the production of winter jackets, to increase the insulation ability of the other clothing items, or to relay higher activity and shorter exposures to the cold environment.

The results obtained and their analysis have a practical use, as they allow to estimate the cold protection effectiveness of textile layers in an assembly, anticipated for the production of winter jackets at the design stage, thus enabling possible changes depending on the conditions of application of the jackets predicted.

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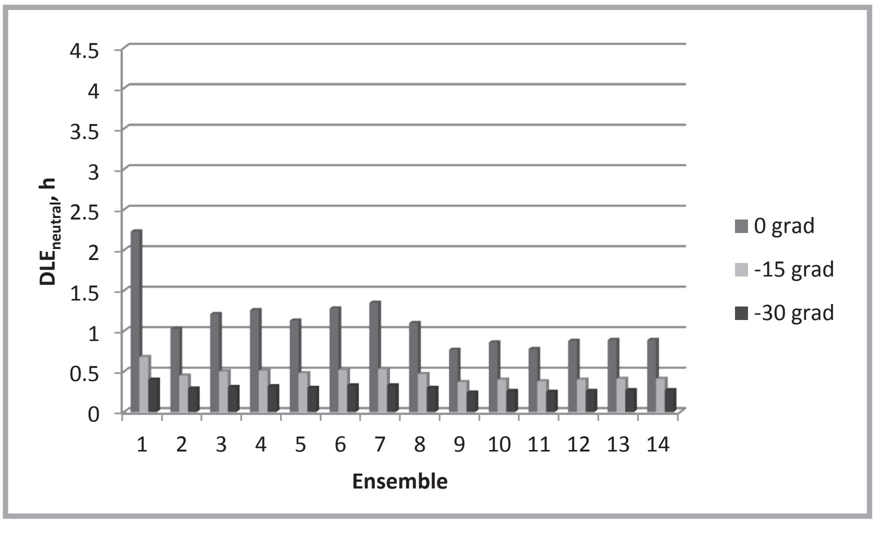

***Figure 6.** Duration of exposure in conditions of thermophysiological comfort for all ensembles.*

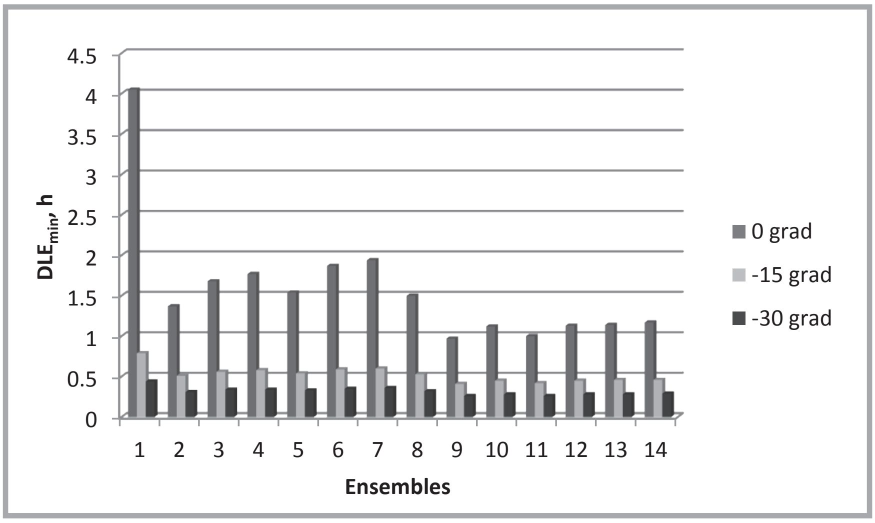

***Figure 7.** Duration of exposure in conditions of constant cooling for all ensembles.*

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