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Aspects of Standardisation in Measuring Thermal Clothing Insulation on a Thermal Manikin

Abstract
The aim of this paper is to analyse the influence on a standing thermal manikin of various factors such as thermal environment parameters (temperature, humidity, velocity/direction of air flow), how heating power is transferred to the manikin, and the time required to reach thermal balance during tests with thermal clothing insulation. Three sets of clothing, designed for protecting before cold, intended for use at very low temperatures (0, -10 and -25 °C) were tested in a climatic chamber on a standing thermal manikin. The results of the tests yielded the following results: 1) methods to control the transfer of heating power to the manikin have a negligible influence on the determined value of clothing thermal insulation, 2) air velocity decreases the tested thermal insulation by 7%, whereas an increase in temperature increases the thermal insulation, 3) temperature in a climatic chamber should be determined in accordance with the anticipated clothing insulation of the clothing ensemble being tested. The tests showed that in order to obtain reliable and accurate results, it is necessary to maintain an appropriate air velocity in the climatic chamber, of around 0.3 to 0.5 m/s, and an appropriate difference in temperatures between the manikin's surface and the environment at a minimum of 12 °C.

Key words: *cold protective clothing, thermal manikin, standardisation of thermal insulation measurements.*

Introduction

The use of thermal manikins to determine the clothing thermal insulation goes back to the 1940s. This method was first developed in the United States, then in Germany, Japan, Canada, Denmark and France [1-3]. Nowadays thermal manikins have unquestionable priority as instruments for determining thermal clothing insulation [4-12]. The number of manikins is still increasing (there are about 100 working thermal manikins in the world) [3-20], as is the scope of their applications. Because they are designed and built by different groups, usually associated with universities or research institutes, an enormous diversity of technical characteristics for these devices exists, resulting from the use of different construction materials, differences in shape, structure and the number of segments.

For scientific purposes, thermal manikins must provide reliable and exact measurements. Irrespective of their great diversification in construction, methods of calculation and procedures must be standardised, which means that the insulation data obtained in tests with the use of different manikins and performed in different laboratories must be comparable within the frames of defined limits related to the same testing conditions.

Objective

The aim of this paper was to acquaint both designers and textile producers with the method of measuring thermal clothing insulation performed on the thermal manikin, but above all to determine those elements of the measurement procedure which significantly influence the value of this parameter and should thus be standardised.

Table 1. *Tested garments and their thermal insulation and water vapour resistance values [16].*

Temperature, °C	Ensemble	Thermal insulation Rct, m^2K/W	Water vapour resistance Ret, m^2Pa/W
0	Polo shirt + pants	0.036	4.66
	jacket	0.152	15.6
	pants	0.115	14.2
	sneakers		
	socks 1	0.087	10.4
	gloves		
	headgear 1	0.168	37.1
-10	polo-neck shirt + pants	0.036	4.66
	jacket	0.152	15.6
	pants	0.115	14.2
	safety boots		
	socks 1	0.087	10.4
	mittens	0.175	30.1
	headgear 1	0.168	37.1
-25	jacket + pants	0.087	10.4
	jacket + trousers	0.351	87.2
	safety boots		
	socks 1	0.087	10.4
	socks 2	0.166	19.3
	mittens	0.175	30.1
	headgear 2	0.331	37.8

Material and methods of calculations

Tested clothing and measurement device

Three double sets of cold protective clothing intended for use in very low temperatures (0, -10 and –25 °C) were tested in a climatic chamber on a standing manikin. The clothing ensemble's characteristics are presented in Table 1 [16].

The tests were performed in a Weiss climatic chamber, type WK23'/40-70, with the following parameters:

- temperature range: -40 °C to +70 °C;
- humidity range: 20% to 90% RH;
- air velocity range: 0.1 to 3 m/s.

Clothing insulation was assessed during testing on a thermal female manikin TM 3.2/R110 named Diana (designed by PT-Teknik, Denmark and manufactured by the Central Institute for Labour Protection, National Research Institute), which is a human phantom in terms of heat exchange via convection, radiation and conduction. It simulates dry heat loss from the human body. Diana is made of 16 electrically independent heating segments which are individually controlled/regulated by a computer system (Figure 1). The temperature-sensing elements (nickel wire) are distributed all over the segments. Measurement of the wiring's resistance gives the mean temperature of the actual body segment.

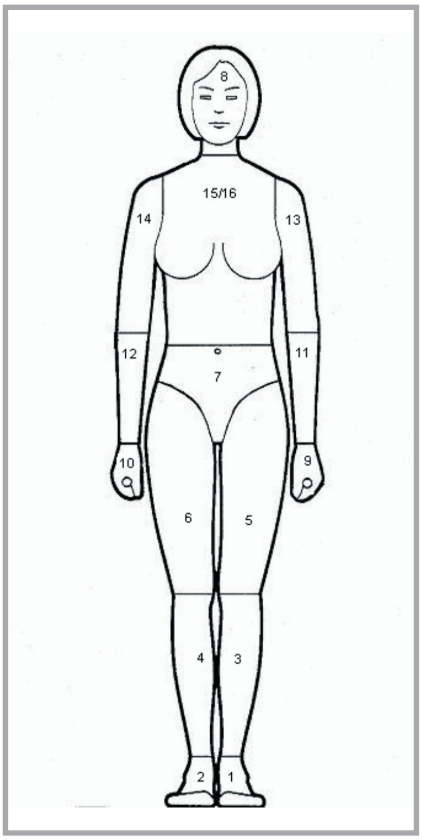

Figure 1. Sections of thermal manikin 'Diana' (1,2 – left, right foot, 3,4 – left, right leg, 5,6 – left, right thigh, 7 – pelis, 8 – head, 9,10 – left, right hand, 11,12 – left, right forearm, 13,14 – left, right upper arm, 15 – chest, 16 – back).

There are two modes by means of which each of the 16 segments can be controlled:

- comfort mode, which is used to maintain a correlation between surface temperature (T_s) and dry heat loss (H_c - equal heating power transferred to the manikin). It is based on Fanger's comfort equation:

  $$(T_s = 36.4 - 0.054H_c$$

- static mode, which is used to maintain a constant surface temperature (T_s).

The manikin software (Manikin 3.x) measures both the surface temperatures and heat losses separately for each of those 16 sections, as well as their average values.

In order to measure the total clothing insulation (I_t), the manikin dressed in the tested ensembles was placed in the climatic chamber. During the tests, ambient conditions were maintained at a constant level; the air temperature (T_a) remained at 5.0 ± 0.2 °C, air velocity at 0.3 m/s and relative humidity at 50%. The average manikin surface temperature (T_s) in the above mentioned conditions was maintained at the level of 34 °C (static mode), hence corresponding to the skin temperature of the human body. Such conditions are in accordance with the requirements of standard EN ISO 15831 'Clothing: Physiological effects: Measurement of thermal insulation by means of a thermal manikin' [19], which states that the air temperature in the climatic chamber must be set at least 12 K below the manikin's mean skin temperature and/or to a value ensuring a minimum heat flux of 20 W/m^2 at each segment of the manikin.

The thermal clothing insulation of each ensemble was calculated by means of the measurements of total heating power transferred to the manikin in order to maintain the required constant surface temperature (either in static or comfort mode) and the measurement of the thermal manikin's surface temperature of (as calculated by the Manikin 3.x programme), according to the requirements of standard EN ISO 15831. When the thermal balance was reached (i.e. a situation in which the average temperature of the manikin's surface (the layer positioned directly at the manikin's surface)and the power transferred to the manikin's heating systems reached constant values) the following variables were recorded continuously:

- the local skin temperatures of each manikin's segment (T_{si}),
- the heating power flow density transferred to each segment (H_{ci}),
- the total heating power transferred to the manikin (H_c), and
- the air temperature in the climatic chamber (T_a).

All the above measurements were taken every 30 seconds for 30 minutes after the system had reached the steady state. The average values of measurements were used to calculate the tested thermal clothing insulation. Each clothing ensemble was tested a minimum of twice, according to the requirements of EN ISO 15831.

Methods of calculating clothing insulation

In order to assess the clothing thermal insulation of each of the three ensembles, two calculation methods were used: serial and parallel, according to standard EN ISO 15831.

Serial model

The total thermal insulation (I_t) of the clothing ensemble is calculated by adding the area-weighted local thermal insulation of the manikin's different body segments. The area factor (f_i) of the manikin section is represented by a quotient of the surface area of the section (a_i) and the total body surface area (A).

$$I_t = \sum_i f_i \left[\frac{(T_{si} - T_a)\cdot a_i}{H_{ci}}\right], \ \frac{m^2K}{W} \qquad (1)$$

$$f_i = \frac{a_i}{A} \qquad (2)$$

The thermal insulation of a nude manikin (I_a) is calculated on the basis of Equation (1) using the measurements of the nude manikin. An effective thermal insulation of the clothing ensemble (I_{cle}) is described by the equation:

$$I_{cle} = I_t - I_a \ , \ \frac{m^2K}{W} \qquad (3)$$

Parallel model

The total thermal insulation (I_t) of the clothing ensemble is calculated by using the total heat flow from the manikin's body:

$$I_t = \frac{(\overline{T}_s - T_a)A}{H_c} \quad , \frac{m^2K}{W} \qquad (4)$$

The average weighted manikin layer temperature ($\overline{T}_s$):

$$\overline{T}_s = \sum_i f_i \cdot T_i \ , K \qquad (5)$$

Influence of environment parameters (temperature, air velocity, humidity, air flow direction) on thermal clothing insulation

In addition to the experiments performed in the conditions presented above, set number 2 (intended for temperature -10 °C) was also tested in the following conditions:

- air temperatures (+22, +15, +5, -15 °C),
- air flow (0.3 m/s, 0.5 m/s, 0.7 m/s),
- air flow directions (front to back; back to front),
- relative humidity (20, 50 and 80%).

First, the temperature in the climatic chamber was changed (from +22 to -15 °C) in order to measure the thermal clothing insulation at four different temperatures (the remaining factors remained constant). Subsequently, using the same method of exposure to different air flows, the flow directions and humidity values on the insulation value were analysed separately.

Estimating the time required for the thermal manikin to reach a steady thermal state with the environment

In order to determine the time necessary for the thermal manikin to attain a steady thermal state with the environment, we used measurements of the heat flow emitted from the manikin surface while testing the thermal insulation of three sets of clothing designed for temperatures of 0, -10 and -25 °C. It was assumed that the steady state is reached when the value of a heat flow does not change over time.

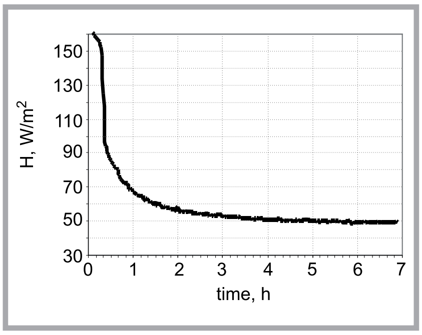

Figure 2. The function representing variation of power flow density H in time t.

Assuming that H is the heat flow density (the power divided by the appropriate area), the density-dependent variation of the flow power H in time t (Figure 2) shows that the power flow density can be approximately described by the following equation:

$$H(t) = H_0 + ce^{-bt} \qquad (6)$$

In this case, H_0 determines the fixed value of the heat flow density (in the sense of the average value) reached after a certain period of time, for which a stabilisation process of heat exchange between the manikin and the environment is accomplished (the form of formula (6) shows that H_0 is reached theoretically in the time $t = \infty$). Tests with thermal manikins show that the fluctuations of heat flow values around H_0, which result from the properties of the automatic system controlling the heating system of the manikin, are close to the random process with definable parameters described by a normal distribution. The course of the temporal variations in measured heat flow density values $H(t)$ from different parts of the manikin shows that practically all of them reach the state of thermal balance with the environment at different times counting from the beginning of measurements. The symmetrical segments of the manikin, i.e. the left and right upper limb or both legs, reach the steady state in a comparable period of time. Therefore the time required for the manikin to reach the steady state should be assumed as the longest of all the times recorded. Usually the parts with the largest surface, i.e. the back and chest, take the longest time to reach the steady state.

Approximating the results of temporal heating flow density variation measurements by the function determined by equation (6) makes it possible to calculate the time (t) when a thermal balance state can be reached with the assumed accuracy:

$$t = \frac{-\ln(\Delta H / c)}{b} \qquad (7)$$

In the present paper, the time (t) for the above mentioned sets of clothing was estimated on the basis of the course of $H(t)$ for the manikin's whole surface and the heat flow density measurements from its back $H_p(t)$. The H_0, c and b parameter values were estimated for the two temporal heat flow density courses determined for each type of clothing. The approximate function (6) was adjusted to

***Table 2.a.** Results concerning heat flow density H_p (manikin's back).*

H_{gr}, W/m²	H_0, W/m²	c	b	T_1, h	T_2, h	T_3, h
70	52.67	56.75	1.356	2.93	3.45	4.68
60	52.62	40.98	1.196	3.06	3.64	5.03
-	-	-	**Mean**	**3.00**	**3.55**	**4.89**

H_0 = 52.66 ± 1.32, value estimated from regression line equation.

***Table 2.b.** Results concerning heat flow density H_c (whole body of manikin).*

H_{gr}, W/m²	H_0, W/m²	c	b	T_1, h	T_2, h	T_3, h
100	81.64	53.65	1.606	2.17	2.61	3.91
90	81.62	42.57	1.468	2.22	2.69	4.12
85	81.57	22.19	1.173	2.23	2.82	4.61
-	**-**	**-**	**Mean**	**2.21**	**2.71**	**4.21**

H_0 = 81.64 ± 0.52, value estimated from regression line equation.

***Table 3.a.** Results concerning heat flow density H_c (manikin's back).*

H_{gr}, W/m²	H_0, W/m²	c	b	T_1, h	T_2, h	T_3, h
50	38.09	41.44	1.169	3.42	4.00	5.15
60	38.17	50.57	1.287	3.30	3.80	4.80
-	-	-	**Mean**	**3.36**	**3.90**	**4.98**

H_0 = 38.14 ± 1.04, value estimated from regression line equation.

***Table 3.b.** Results concerning heat flow density H_c (whole body of manikin).*

H_{gr}, W/m²	H_0, W/m²	c	b	T_1, h	T_2, h	T_3, h
72	66.84	53.11	1.528	2.40	2.86	4.10
70	66.58	18.17	0.939	2.78	3.52	5.54
-	-	-	**Mean**	**2.59**	**3.19**	**4.82**

H_0 = 66.59 ± 0.22, value estimated from regression line equation.

***Table 4.a.** Results concerning heat flow density H_c (manikin's back).*

H_{gr}, W/m²	H_0, W/m²	c	b	T_1, h	T_2, h	T_3, h
60	26.31	51.18	1.027	4.5	5.1	6.1
52	26.14	46.35	0.948	4.7	5.5	6.5
40	25.61	32.52	0.731	5.7	6.6	7.9
-	-	-	**Mean**	**4.97**	**5.7**	**6.8**

H_0 = 25.79 ± 1.44, value estimated from regression line equation.

***Table 4.b.** Results concerning heat flow density H_c (whole body of manikin).*

H_{gr}, W/m²	H_0, W/m²	c	b	T_1, h	T_2, h	T_3, h
60	48.92	28.43	0.777	4.3	5.2	7.3
55	48.54	19.37	0.597	5.0	6.2	8.8
-	-	-	**Mean**	**4.7**	**5.7**	**8.0**

H_0 = 48.89 ± 0.30, value estimated from regression line equation.

measurement data but not throughout the whole range of variability. The results from the initial period of measurements (i.e. about 40 to 50 minutes) were neglected, due to a sudden fall in the heat flow density value emitted from the manikin surface; only the final stage, when the manikin/environment system was at a steady thermal state, was analysed. Therefore, a limit level of heat flow density (H_{gr}) was accepted for each ensemble, and measurements exceeding this level were omitted in the approximation.

Results and discussion

Estimating the time required for the thermal manikin to reach a steady thermal state with the environment

The average results of measurements of three sets of clothing are presented in Tables 2.a & 2.b to 4.a & 4.b.

Table 2.a, & 2.b presents the results for protective clothing for work at 0 °C temperature; I_T = 2.27 clo (parallel), 2.53 clo (serial), T_a = 5 °C, V_a = 0.27 m/s.

Table 3.a, & 3.b presents the results for protective clothing for work at -10°C temperature; I_T = 2.79 clo (parallel), 3.16 clo (serial), T_a = 5.2 °C, V_a = 0.3 m/s.

Table 4.a, & 4.b presents the results for protective clothing for work at -25°C temperature; I_T = 3.76 clo (parallel), 4.38 clo (serial), T_a = 5.44 °C, V_a = 0.32 m/s.

Remark: One clo is defined as the thermal insulation necessary to maintain the thermal balance of a seated subject in a room with the following ambient parameters: air velocity equal to 0.1m/s, air and wall temperature 21 °C, and humidity under 50% RH. Under these conditions, 1 clo corresponds to the insulation of a clothing ensemble equal to 0.155 m^{2}K/W.

The estimated times necessary for the thermal manikin to reach thermal balance with the environment for selected sets of protective clothing are presented in Tables 2, 3 and 4.

An analysis of the regression line equation proved to be an efficient method of estimating the H_0 value, and its course approximating a chosen temporal period of measurement data could be used as a criterion for H stability reached over time. When the regression line became almost parallel to the time axis, a steady thermal state has been reached. In this case, the H_0 value could be calculated from the regression line equation in the middle of the analysed time interval. Based on the function parameters (6) included in Tables 2, 3 and 4, the time after which the difference $\Delta H = H(t) - H_0$ reached the assumed value was calculated from the formula (7). The following symbols were adopted:

τ_1 – the time determined for
$\Delta H = 0.02H_0$
τ_2 – the time determined for
$\Delta H = 0.01H_0$
τ_3 – the time determined for
$\Delta H = 0.1$ W/m^2

The values T_i, i = 1, 2, 3 obtained from the calculations are presented in Table 2, 3, and 4. The times T_i, i = 1, 2, 3 estimated according to the method presented above give an idea of the relationship between the precision of determining the thermal clothing insulation and the time of measurements; the higher the value of the tested thermal insulation, the longer the manikin took to reach a state of thermal balance with the environment. This time could thus be shortened by reducing the difference between the manikin's surface temperature and the environment, in accordance with the anticipated clothing insulation.

The dynamism of measurement $I_T(t)$ reaching the limit value over time was another important observation drawn from the experiments. The value $I_T(t)$ was calculated using $H(t)$ measurement results. In this case:

$$I_T(t) = \frac{(T_s - T_a)}{H(t)} = \frac{(34-5)}{H(t)} = \frac{29}{H(t)} \quad (8)$$

where

$$I_T(H_0) = \frac{29}{H_0}$$

The variation of the relation $\frac{I_T(t)}{I_T(H_0)} \cdot 100$ determined for the tested ensemble intended to be used at 0 °C over time (t) is presented in Figure 3, as an example.

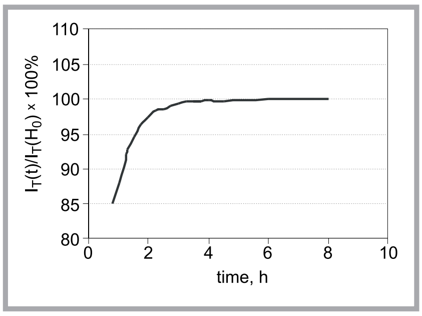

Figure 3. *Dependence of insulation quotient and time.*

Influence of environment parameters (temperature, air velocity, humidity, air flow direction) on thermal clothing insulation

The average calculations of clothing insulation for three sets of clothing are presented in Table 5.

The reproducibility of the thermal insulation test results was high; the mean standard deviation for the values given in m^{2}K/W was 0.012, while for values given in clo it was 0.075.

The results achieved for clothing ensemble number 2, where climatic conditions were changed, are presented in Figures 4 to 6:

As can be seen from the course of the line joining the values of thermal clothing insulation and different air temperatures in the climatic chamber (Figure 4) the thermal clothing insulation increased together with the increase in air temperature, whereas the surface temperature of the manikin remained constant. Together with the increase in air velocity, the tested thermal insulation decreased by 7% (Figure 5), whereas the effects of humidity (Figure 6) and direction of air flow (Figure 7) were negligible.

Summary and conclusions

The results of tests described above showed that:

- the methods of controlling how heating power is transferred to the manikin (static and comfort modes) have

Table 5. *Results of clothing insulation calculation.*

Ensemble intended for:	Total clothing insulation			
	serial model ± SD, m^{2}K/W	serial model ± SD, clo	parallel model ± SD, m^{2}K/W	parallel model ± SD, clo
0 °C	0.386 ± 0.01	2.48 ± 0.08	0.346 ± 0.01	2.23 ± 0.08
-10 °C	0.484 ± 0.01	3.12 ± 0.05	0.428 ± 0.01	2.77 ± 0.04
-25 °C	0.687 ± 0.01	4.43 ± 0.09	0.577 ± 0.01	3.72 ± 0.05

negligible influence on the thermal clothing insulation;

- air velocity decreases the tested thermal insulation by 7%, whereas the influence of other parameters (humidity, air flow direction) can be discounted;
- conditions in the climatic chamber, especially temperature, should be established in accordance with the anticipated thermal insulation of a tested set of clothing.

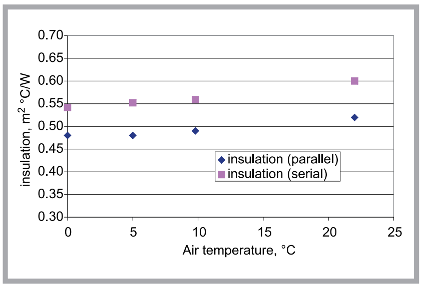

Figure 4. *Influence of air temperature on thermal clothing insulation for two calculation models.*

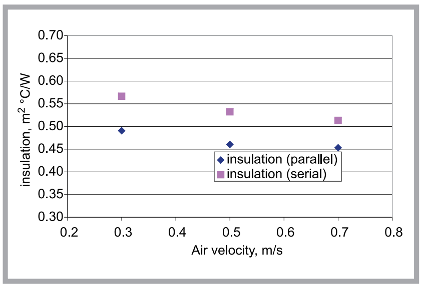

Figure 5. *Influence of air velocity on thermal clothing insulation for two calculation models.*

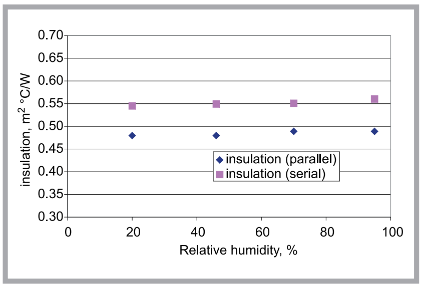

Figure 6. *Influence of relative humidity on thermal clothing insulation for two calculation models.*

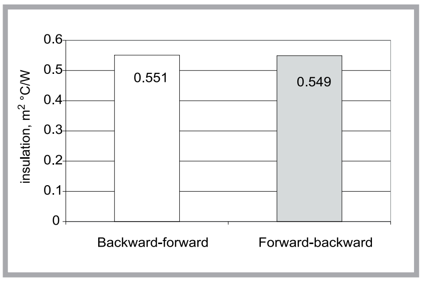

Figure 7. *Influence of air direction on thermal insulation.*

Our experiments showed that the thermal clothing insulation increases together with the temperature increase because of the lower difference between the air temperature and the manikin's surface temperature. However, the temperature difference between the air temperature and that of the manikin should also be maintained (as is reflected in standard EN ISO 1583, which states that the air temperature in the climatic chamber is to be set at least 12K below the manikin's mean skin temperature and/or to a value ensuring a minimum heat flux of 20W/m^2 at each segment of the manikin).

Clearly, clothing insulation does not depend only on the temperature difference. It is recognised that another important factor influencing the thermal insulation of clothing is ventilation (the so-called 'pumping effect'), which can be assessed using a moving thermal manikin [16 - 18]. Insulation obtained on a motionless (standing) manikin is higher comparing to the tests performed on a moving manikin.

As already mentioned in the introductory part of this paper, many laboratories in the world test thermal clothing insulation using various thermal manikins. Although international standard EN ISO 13531 clearly specifies the methodology for performing this test, so far no deeper analysis has been carried out to find out the reasons for the differences in results for insulation values obtained by different laboratories. On the basis of the tests described above, it transpires that the following factors have a significant influence on the quality of results obtained: air velocity, the temperature difference between the manikin's surface temperature and the air temperature in the climatic chamber, and the time necessary to reach the steady state between the thermal manikin and the environment. To this end, the authors of the paper suggest the introduction of the following requirements:

1. decreasing the admissible range of air velocity from 0.3 - 0.7 to 0.3 - 0.5 m/s as standard procedure, taking into consideration the decrease in thermal clothing insulation (I_T) of 7% caused by the air movement in the range of 0.3 - 0.7 m/s;
2. increasing the temperature range between the manikin surface and the environment proportionally to the thermal clothing insulation, so that the time required to reach the thermal balance between the manikin and the environment is shortened.

Acknowledgment

The publication was prepared as part of the project 'The creation of a national centre for research on reduction of occupational risk for workers exposed to cold and heat' carried out within the 2nd stage of the National Programme on 'Adaptation of working conditions in Poland to EU standards'. Financial assistance for 2005-2007 has been provided by the Ministry of Labour and Social Policy in the scope of tasks related to the services of the State. The main coordinator – is the Central Institute for Labour Protection, the National Research Institute.

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Received 12.01.2006 Reviewed 03.10.2006

The Institute of Natural Fibres

in Poznań participated in the **55th World Exhibition of Innovation, Research and New Technology EUREKA 2006**, held in **Brussels** on 23-27 November 2006, and in the **International Invention Fair** on 2-11 December 2006 (the exhibition was organised by the **Korea Invention Promotion Association in Seoul**).

The Institute was granted 6 awards for its inventions: 3 gold and 3 silver medals and the Minister of Economy's Cup for the invention presented under the title of 'Method and device for measuring the twist of yarns'.*)

The gold medals were given to:
- the team of inventors **Ryszard Kozłowski, Krzysztof Bujnowicz, Bożena Mieleniak** and **Alojzy Przepiera** for VERBLOCKER, a rigid fire barrier composite;
- the team of inventors **Ryszard Kozłowski, Wanda Konczewicz** (INF Poznań) and **Jan Wojtysiak** and **Władysław Podsiedlik** (ITE in Łódź) for the invention presented under the title of 'Device for processing fibrous raw materials and the processing method';
- **Zdzisław Czaplicki** for 'Method and device for measuring the twist of yarns'. *)

The silver medals were given to:
- the team of inventors **Jan Gąsiorek** and **Marian Kaczmarek** for 'Procedure and system for glycerin waste management: liquids, quasi-solids and solids forming by bio-esters production from vegetable oils and animal fats';
- the team of inventors **Ryszard Kaniewski, Jadwiga Kozłowska** and **Józef Gągało** for 'Flaxseed butter and the method of its production';
- **Natalia Sedelnik** for 'Flax core spun yarn and the flax core spun yarn production method'.

Only the inventions that received gold medals in Brussels were presented in Seoul, Korea. These inventions were awarded 2 gold and 1 bronze medals.

The gold medals were given to:
- the team of inventors **Ryszard Kozłowski, Krzysztof Bujnowicz, Bożena Mieleniak** and **Alojzy Przepiera** for VERBLOCKER, a rigid fire barrier composite;
- **Zdzisław Czaplicki** for 'Method and device for measuring the twist of yarns'. *)

The bronze medal was given to the team of inventors **Ryszard Kozłowski, Wanda Konczewicz** (INF Poznań) and **Jan Wojtysiak** and **Władysław Podsiedlik** (ITE in Łódź) for their 'Device for processing fibrous raw materials and the processing method.'

*) The invention awarded gold medals in Brussels and Seoul by Zdzisław Czaplicki was described and published in Fibres & Textiles In Eastern Europe, Volume 14, No.1 (55), 2006 ISSN 1230-3666.

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