

Thermal Manikin Measurements—Exact or Not?

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According to the European prestandard ENV 342:1998 [1], the thermal insulation of cold-protective clothing is measured with a thermal manikin. Systematic studies on the reproducibility of the values, measured with different types of clothing on the commonly used standing and walking manikins, have not been reported in the literature. Over 300 measurements were done in 8 different European laboratories. The reproducibility of the thermal insulation test results was good. The coefficient of variation was lower than 8%. The measured clothing should fit the manikin precisely, because poorly fitting clothing gave an error in the results. The correlation between parallel and serial insulation values was excellent and parallel values were about 20% lower than serial ones. The influence of ambient conditions was critical only in the case of air velocity. The reproducibility of thermal insulation test results in a single laboratory was good, and the variation was lower than 3%.

protective clothing, thermal insulation, cold protection, calculation method

1. INTRODUCTION

According to the European prestandard ENV 342:1998 [1] and International Organization for Standardization (ISO) standards [2, 3], the thermal insulation of cold-protective clothing is measured with a thermal manikin and the value is attached to the clothing. Based on the thermal insulation value, it is possible to

estimate the conditions (temperature, activity) in which the clothes provide appropriate protection and comfort [3, 4]. A thermal manikin is an instrument which simulates a human being as regards dimensions; it measures heat loss through the clothing systems dressed on it. As body movements cause air movement within the clothing and thereby increase convection and ventilation, it

The SUBZERO project was financially supported by the European Commission (contract G6RD-CT-2000-00274). All partners in the project are sincerely thanked for their good cooperation.

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has been agreed that thermal insulation measurements shall be performed by a moving manikin whose arms and legs make a pendulum movement simulating walking at a specified speed [1, 2].

Thermal manikins have been used in a number of laboratories for decades to measure the thermal insulation of clothing systems. Although there are some differences in the basic construction of manikins, the heating systems, shell materials, dimensions and the measurement principles are similar. It has therefore been presumed that the results from different laboratories are comparable, as long as the garments fit the manikin correctly. However, no systematic studies of the reproducibility of the values, measured with different types of clothing on the commonly used standing and moving manikins, have been reported in the literature [5]. Such studies have, however, been made with standing sweating manikins [6]. Hence one of our objectives was to establish the reproducibility and independence of a manikin type on the thermal insulation value, measured with a moving manikin according to ENV 342:1998 [1]. Also the differences in thermal insulation values arising from the calculation principle and the influence of ambient conditions, airflow and humidity on the thermal insulation value had to be evaluated.

This report is part of the a larger European Union (EU) project, i.e., the European SUBZERO project, performed by a consortium of seven leading clothing physiology research institutes and five clothing manufacturers to provide data for the revision of ENV 342:1998 [1]. The objective of the project was to define the following important factors concerning the measurement of cold protective clothing using thermal manikins:

- The reproducibility of the thermal insulation test results, measured in accordance with the

method referred to in ENV 342:1998, using different types of thermal manikins (shell material, size, number of separately heated body segments, movement mechanism, dimensions);

- The relationship between the physically measured thermal insulation values of cold protective clothing and the corresponding physiological reactions of the human test subjects;
- The influence of sweat evaporation and condensation on heat transmission properties;
- The influence of ambient conditions on the thermal insulation value.

2. METHODS

A set of four clothing ensembles was tested under different ambient conditions in eight European laboratories participating in the study. Table 1 shows the test garments and Table 2 the ensembles used in the study. The garments were chosen from the participating garment manufacturers' catalogues to give adequate protection in the respective environmental temperatures. After a preliminary manikin test in one laboratory and subsequent predictive calculations, the final choice of garments was made. Two versions of the outer garments were tested, i.e., with and without a water-impermeable membrane.

The parameters of the manikins participating in the study are specified in Table 3. Measurements were performed with the manikins standing and moving, and two replications of each test were conducted. Altogether 380 measurements were done and statistically concluded.

Two principles can be used for the calculation of thermal insulation [1]. One is based on the measurement of total thermal insulation by summation of the local area-weighted thermal insulations (serial

TABLE 1. Tested Garments and Their Thermal Insulation Values (Material Combinations) Measured According to ISO 11092:1993 [7]. The Barrier is the Water-Impermeable Membrane in the Garment

Garment	Description	Thermal insulation R_{ct} ($m^2 \cdot K/W$)
Underwear 1	polo shirt + pants	0.036
Underwear 2	jacket + pants	0.087
Intermediate	jacket	0.152
Outer garment 1	jacket	0.183 (with barrier)
	trousers	0.123 (with barrier)
Outer garment 2	jacket + trousers	0.351 (with barrier)
Outer garment 3	jacket	0.362 (with barrier)
	trousers	0.266 (with barrier)
Footwear 1	sneakers (own)	
Footwear 2	safety boots	
Socks 1		0.087
Socks 2		0.166
Handwear 1	gloves	
Handwear 2	mittens	0.175
Headgear 1		0.168
Headgear 2		0.331
Headgear 3	balaclava	0.044

TABLE 2. Tested Garments and Temperature of the Environment Equivalent to the Thermal Insulation of the Clothing Ensembles (A, B, C, D) According to the IREQ (Insulation Required) Index

Garment		Temperature of the Environment			
		0 °C	-10 °C	-25 °C	-50 °C
		Ensemble A	Ensemble B	Ensemble C	Ensemble D
Underwear	1	x	x		
	2			x	x
IntermediateB			x	x	x
Outer garment	1	x	x		
	2			x	
	3				x
Footwear	1	x			
	2		x	x	x
Socks	1	x	x	x	x
	2			x	x
Handwear	1	x			x
	2		x	x	x
Headgear	1	x	x		
	2			x	x
	3				x

TABLE 3. Specifications of Participating Manikins

Partner No.	Shell	Size	Number of Segments	Movement	Surface (cm ²)	Height (cm)	Chest (cm)
1	Plastic	52 (medium)	18	–	1.72	172	100
2	Metal	52 (medium)	15	Mechanic	1.85	171	93
3	Plastic	Medium	35	Mechanic	1.67	173	84
4	Plastic	52 (medium)	18	Pneumatic	1.77	171	99
5 a, b	Metal	52	20	Mechanic	1.89	176	96
6	Plastic	38 (female)	16	Mechanic	1.46	174	92
7	Plastic	38 (female)	16	Mechanic	1.46	168	93

Notes. Laboratories: 1—Technical Research Centre of Finland, Finland; 2—Bekleidungsphysiologisches Institut Hohenstein, Germany; 3—Institut Français du Textile et de Habillement, France; 4—National Institute for Working Life, Sweden; 5—Finnish Institute of Occupational Health (2 laboratories), Finland; 6—SINTEF Health Research, Norway; 7—Central Institute for Labour Protection – National Research Institute, Poland.

model). The other method determines the thermal insulation as an area-weighted average of the local insulations (parallel method). The equations for the calculation of the two alternatives are:

serial method

$$I_{t, \text{ser}} = \sum_i f_i \left[\frac{(T_{si} - T_a) \cdot a_i}{H_{ci}} \right] \frac{m^2 \cdot ^\circ K}{W},$$

parallel method

$$I_{t, \text{par}} = \frac{\left[\left(\sum_i f_i \cdot T_{si} \right) - T_a \right] \cdot A}{\sum_i H_{ci}} \frac{m^2 \cdot ^\circ K}{W},$$

$$\bar{T}_s = \sum_i f_i \cdot T_{si} \quad ^\circ K,$$

where f_i —area factor of section i of the manikin, T_{si} —local surface temperature of section i of the manikin in $^\circ K$, T_a —air temperature in environmental chamber in $^\circ K$, a_i —surface area of section i of the manikin in m^2 , H_{ci} —local heating power fed to section i of the manikin in W , T_s —mean surface temperature of the manikin in $^\circ K$, A —total body surface area of the manikin in m^2 , H_c —total heating power fed to the manikin in W .

ENV 342:1998 [1] states that the air temperature at which the measurement of thermal insulation shall be done, is at least $10^\circ C$ below the manikin's mean temperature. For a

cold weather clothing ensemble with high thermal insulation, heat loss is usually very low if the temperature gradient is small. In order to minimise the measurement error, it is preferable to do the test at a lower ambient temperature. Air flow (direction and velocity 0.3–1 m/s) and air humidity (20–80%) in the climatic chamber also vary between the laboratories, and this is believed to influence the measured thermal insulation values. Are these conditions significant concerning the measurement results?

3. RESULTS AND DISCUSSION

3.1. Measuring Time

During the work process in the different laboratories, a central practical question concerned measurement time. Under normal circumstances, the thermal balance or steady state condition, in which heating power changes less than 2%, is reached in 1 hr, and the result can be calculated in relation to the results of the last 10 min. The plastic manikin stabilizes clearly faster. With the lightest ensemble, the stabilization takes about 10 min and with the winter ensemble about 30 min. When measurements are started with a cold manikin, the time needed for thermal balance

can be more than 3 hrs. Hence, as most standards mention, it is sufficient to collect data for 30 min after the system has reached the steady state.

3.2. Reproducibility of Thermal Insulation Test Results

As an example, the results of the thermal insulation measurements with standing manikins conducted in the different institutes are presented in Figure 1.

conditions the standard error was as high as 15% (Table 4). A few tests with different gait lengths in walking conditions increased the differences.

Although the total variation in the thermal insulation values was on an acceptable level, some systematic differences between the laboratories were noted. Laboratory 2 generally showed low values and laboratory 6 higher values. This was suspected to be due to differences in the size of the garments in

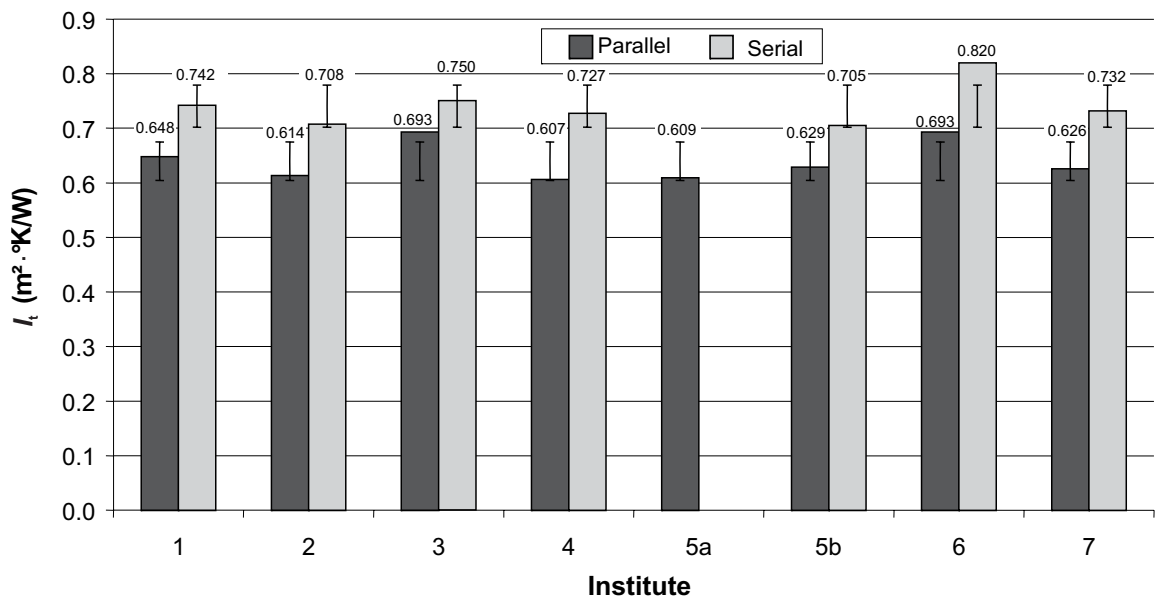


Figure 1. The average value of total thermal insulation in eight different laboratories for ensemble 4, stationary condition. Average values and standard deviations shown. Notes. Laboratories: 1—Technical Research Centre of Finland, Finland; 2—Bekleidungsphysiologisches Institut Hohenstein, Germany; 3—Institut Français du Textile et de Habillement, France; 4—National Institute for Working Life, Sweden; 5—Finnish Institute of Occupational Health (2 laboratories), Finland; 6—SINTEF Health Research, Norway; 7—Central Institute for Labour Protection – National Research Institute, Poland.

Calculated as a percentage, the standard deviation (*SD*) of parallel measurement results was almost the same with standing and walking manikins, and with low and high insulation clothing. The *SD* was nevertheless much higher in the case of serial results when a walking manikin was used. The coefficient of variation (*SD*/average %) in stationary conditions was lower than 9%, using both parallel and serial models. In walking

relation to the size of the manikin. After the discrepancy was brought up, it was also tested. It turned out that clothes four sizes larger than required gave 10% higher insulation values.

The measured thermal insulation I_a of a nude manikin in stationary conditions was $0.090 \pm 0.005 \text{ m}^2\cdot\text{°K/W}$ and $0.094 \pm 0.004 \text{ m}^2\cdot\text{°K/W}$ with the parallel and the serial method, respectively. A nude manikin gave lower

TABLE 4. Coefficient of Variation (%) of the Total Insulation of Different Ensembles in Ambient Temperature +5 °C Calculated With Parallel and Serial Models, N = 8

Ensemble	Stationary (%)		Walking(%)	
	Parallel	Serial	Parallel	Serial
A	8.2	8.6	6.0	5.7
B	6.7	7.4	5.1	5.6
C	4.4	4.2	7.5	6.3
D	5.5	5.2	4.7	14.5
Nude	5.9	5.1	9.5	8.1

standard deviation values than a clothed manikin. The differences in the basic thermal insulation values between the laboratories were therefore similar to the total insulation values.

3.3. Effect of Calculation Method

The thermal insulation calculated by serial model was always higher than by the parallel model (Figure 2). The serial thermal insulation ($I_{t,s}$) was

$$I_{t,s} = 1.20 I_{t,p} - 0.02 \text{ m}^2 \cdot \text{°K/W},$$

where $I_{t,p}$ is parallel insulation value. Standing and walking conditions gave nearly the same measurement results, and there were no differences between the institutes. The correlation between the values was high ($R^2 = .99$) for these garments, but can be expected to be lower for ensembles in which the insulation is less evenly distributed.

3.4. Influence of the Control System on Surface Temperature

The difference between the two control modes, i.e., a constant surface temperature by the proportional integral method (PI), and a comfort mode modeling a varying surface temperature, was small. The comfort control mode gives greater insulation (2%) than the PI control mode when parallel calculations are used, but less insulation (1%) when serial calculations are used. The difference is explained by the fact that in the comfort mode the extremities have lower temperatures than the head and trunk. Hence some internal heat transfer occurs from one segment to the adjacent ones.

3.5. Effect of the Clothing Area Factor f_{cl}

In order to calculate the intrinsic insulation of clothing, the total and adjacent air layer

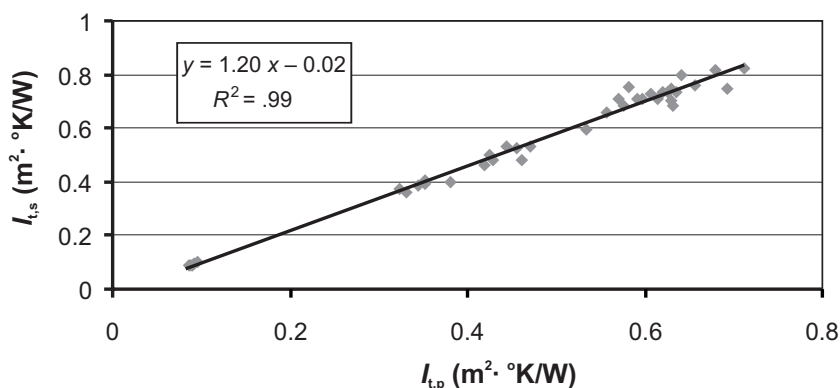


Figure 2. The correlation between serial and parallel thermal insulation values, stationary condition, four clothing ensembles, eight laboratories, N = 32.

insulation and the area factor giving the relationship between the clothing and body area should be known. The following three methods were used to define the clothing area factor f_{cl} : surface temperature, circumference and photography. In the surface temperature method the surface temperature of the clothing was scanned with infrared equipment. In the circumference method a tape measure was used to determine the relationship between the body and clothing measures. In the photography method the calculations were based on the pictures of the manikin, both with and without clothing. Depending on the method, the clothing area factor varied less than 8%. The method affected less than 1% of the intrinsic insulation of the clothing. By using the total insulation instead of the intrinsic insulation in the formula f_{cl} , we can reject the iteration; the error in the intrinsic insulation is thus lower than 1%. We therefore concluded that the clothing area factor was not needed for cold protective clothing.

3.6. Influence of Environmental Conditions

The influence of air velocity (0.3–0.7 m/s) on the total thermal insulation was evaluated in three laboratories (Figure 3). The insulation decreased by 3–6%, when air velocity increased. The decrease was 6% when using the parallel calculation method and 3% when using the serial method. The error for the total insulation is lower than $\pm 1.5\%$ of the mean value in the velocity range of 0.3–0.5 m/s. The decrease due to wind was greatest in the head, being about 20%.

The influence of airflow direction in the climatic chamber (forward-backward, backward-forward, up-down, down-up, forward-up) was evaluated in one laboratory. At low air velocity (0.3 m/s) the direction had a 6% effect on the total thermal insulation.

When the flow was directed along the longitudinal axis of the manikin, the forced convection current affected the whole surface area of the clothing, as opposed to airflow coming from the front. The effect of the wind blowing from the head down on total insulation was 6% lower than the effect of the air blowing

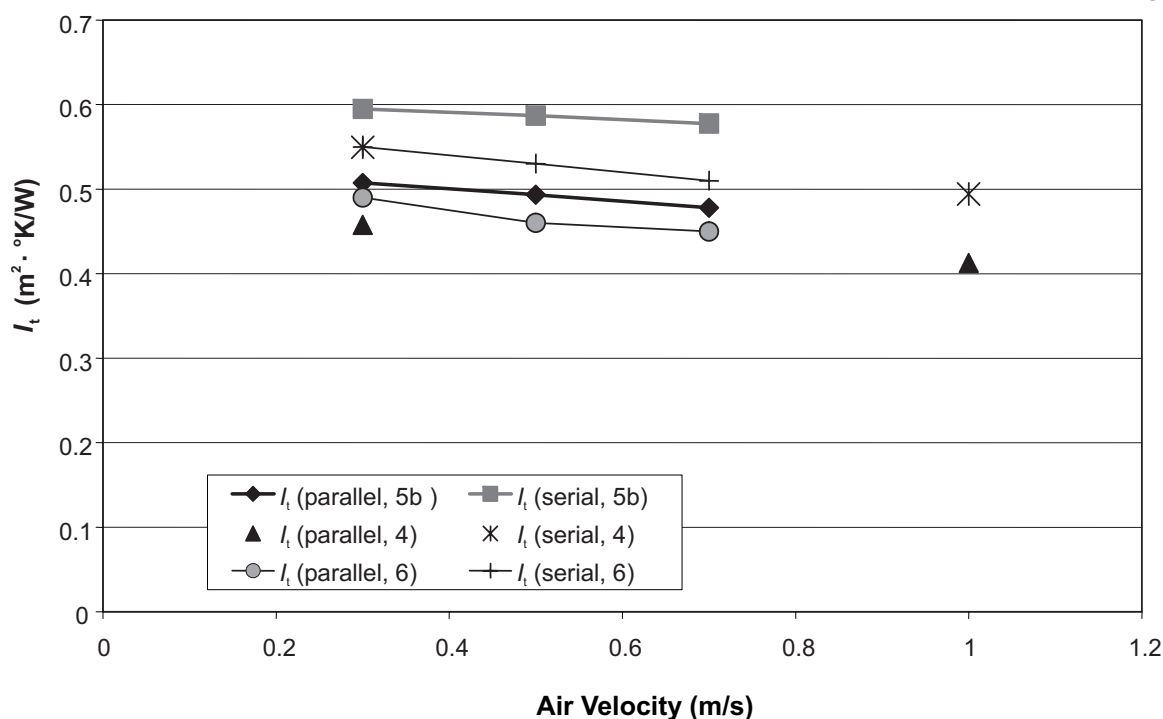


Figure 3. Influence of air velocity on total thermal insulation in three laboratories, stationary conditions.

from the front. The direction of the wind and the direction of the convection current are important at low velocities. The warm air convection is always upwards and that of cold air downwards. At higher velocities the natural convection has no effect on the total convection, and the wind had no effect on the total insulation depending on air direction.

The conclusion was that to keep the error in the results of I_t lower than 5%, the airflow can be directed from the front, or back, or downwards. The air velocity should be in the range of 0.3–0.5 m/s.

The influence of the ambient temperature (+20 ... –25 °C) on the total thermal insulation was evaluated in two laboratories. Its effect on insulation depended on the accuracy of the power measurements. A relatively high ambient temperature means low heating power, and small errors in the power measurements may cause differences in insulation values. At temperatures below zero, the behaviour of I_t was no longer linear, due to the possible dew point and freezing processes. Also the temperature gradient of the garments causes a slight decrease in insulation.

The conclusion was that in order to have a minimal 5% error (<5%) in I_t , the ambient air temperature should be in the range of –15 ... +15 °C. The measuring temperature should be selected so that the power measurement accuracy can be guaranteed at all of the used power levels. A good method to determine a sufficient temperature gradient is to define a minimum heat flux from every zone. The influence of humidity (20–80% RH) on the total thermal insulation was negligible.

4. CONCLUSION

Because there is variation in the construction of the manikins and in the ambient conditions, it is important to evaluate repeatability,

reproducibility and between-laboratory variance. Also discussion of the methods for calculating insulation and their relevance is important.

The reproducibility of the thermal insulation test results was as good as in an earlier study carried out by the manikin laboratories in 1998 [5], the coefficient of correlation being lower than 8%. Only one case was out of range due to the too large size of the clothes. Clothes that were four sizes larger than required gave 10% higher insulation values. The size of the garments on the thermal manikin is therefore a critical factor, and the testing laboratory has to make sure that it is correct. The correlation between the parallel and serial insulation values was excellent, and $I_{t,p}$ was about 20% lower than $I_{t,s}$.

Deviations in the local insulation values of the different manikin segments were higher than in the total insulation values. The meaning of the local differences should be understood better by the customers, when information is given to them. Local values should be applied only in the development work or in testing instruments. The deviations in walking conditions were normally lower than in standing conditions, and the observed differences related to the clothing size and/or step length. The clothing area factor f_{cl} affected I_{cl} less than 1%. If the area factor correction of the insulation is needed, this can be done by a simple calculation process or by simple circumference measurements.

The influence of the heating regulation system on the insulation values was minimal. This means that both comfort and normal control systems can be used. The effect of ambient conditions was critical only in the case of air velocity, which should be defined, e.g., between 0.3 and 0.5 m/s. Also the direction of airflow affected the insulation values, usually by less than 5%. Air temperature should be

cool enough to keep the control unit working actively. Air humidity was not a critical parameter. All of the parameters were evaluated by the criteria to keep the deviation in the insulation results due to individual ambient parameter to less than 5%. The criteria are obviously stricter when we calculate the maximum error caused by all the different parameters together. That is why instructions should be given in the manikin standard describing the ambient thermal parameters.

The study showed that none of the manikin measurement options (walking/parallel, walking/serial, standing/parallel, standing/serial) gave results which in all conditions would be unambiguously most reliable for predicting thermal protective properties. The influence of ventilation was assessed by measurement with a walking manikin. However, it would be most informative to have both standing and walking values marked in cold-protective clothing.

Some manikins are not equipped with a walking mechanism, and measurements with the walking manikin caused problems in some laboratories, particularly when the manikin wore very thick clothing ensembles. Data from the measurements nevertheless showed that differences between the walking and standing tests varied between the ensembles. It was therefore agreed that the primary proposal of the project group was that both walking and standing measurements should be performed, and both values marked in the clothing.

The possible influence of washing and wearing on the cold-protective properties is mentioned in the introductory paragraph of ENV 342:1998 [1]. However, thermal insulation tests are performed on new garments. If customers buy cold-protective systems for particular conditions, it is important that the protective properties remain throughout the entire period of usage. Therefore, at least an optional additional test after a number of

washing cycles is recommended. The general view of the manufacturers was that ENV 342:1998 is difficult to understand and use, and also to pass on the information to the users.

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