

THERMAL INSULATION MEASUREMENTS WITH A MOVABLE THERMAL MANIKIN

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INTRODUCTION

The assessment of the thermal insulation of clothing is of great significance whenever the study of human thermal environments is foreseen. Several standards address the measurement specifications of the thermal resistance by means of a thermal manikin. In most of the standards and research studies priority has been given to the study and evaluation of the thermal insulation in a static condition, i. e. with the manikin standing still. The evaluation of the dynamic insulation has thus deserved less attention, despite of its recent growing interest.

The study of the thermal insulation of clothing in a dynamic condition is a very complex challenge. The clothing, garments and ensembles, have openings which make possible air exchanges with the environment. Although this effect is always present, when movement occurs the heat transfer by convection between the skin surface and the clothing and within the clothing is significantly increased and the insulation is changed. This phenomenon is usually called “*Pumping Effect*”. In addition, the body posture, the activity level, the air velocity, the accumulation of sweat, the compression, thickness, the number of layers and the fit of the clothing may also change the thermal insulation significantly.

However, the determination of these several influences either combined or even separately, is very difficult, thus being still considered in some actual standards in a very simple way. The development of thermal manikins capable of assuming different body postures and of simulating walking movements represents an important contribution in obtaining realistic thermal insulation values, as they allow a more correct assessment of the heat transfer when the dynamic phenomena are to be analysed. As a consequence and since the thermal insulation values obtained in the static standardized posture have indeed a limited relevance, this issue represents an important area of research within the scientific community, which now deserves the attention of several research teams. The present work is aimed to perform a comparative analysis between the results obtained in both static and dynamic conditions for which an original mechanism capable of simulating realistic walking movements was developed. The measurements were done with 9 clothing ensembles and the results are presented and discussed for the basic, effective and total clothing insulations.

METHODS

To calculate the thermal resistances of a given ensemble or garment several expressions and definitions are proposed in the literature and the clothing insulation can be presented in terms of the total clothing insulation (I_T), the effective clothing insulation (I_{cle} for ensembles and I_{clu} for

garments) and the intrinsic or basic clothing insulation (I_{cl} for ensembles and I_{cli} for garments) (ISO 9920 2007). The total clothing insulation, I_T , i.e., the insulation from the skin surface to the environment, including the effect of the increased surface area (f_{cl}) and the resistance at the surface of the clothed body, the effective clothing insulation, I_{cle} , consisting of the difference between I_T and I_a , and the intrinsic or basic clothing insulation, I_{cl} , defined as the insulation from the skin to the clothing surface, are calculated by the equations:

$$I_T = \frac{\bar{t}_{sk} - t_o}{\bar{Q}_s} ; \quad I_{cle} = I_T - I_a ; \quad I_{cl} = I_T - \frac{I_a}{f_{cl}} \text{ [m}^2 \cdot \text{°C/W]}$$

where \bar{t}_{sk} [°C] and \bar{Q}_s [W/m²] are the mean skin temperature and the sensible heat flux obtained by area weighing, I_a is the thermal insulation of the air layer [m²·°C/W] and t_o is the operative temperature [°C]. The f_{cl} factor is calculated according to the following expression (McCullough et al., 1985):

$$f_{cl} = 1 + 1,97 \times I_{cl} \quad \text{[m}^2 \cdot \text{°C/W]}$$

To calculate the equivalent thermal resistance of the whole body three calculation methods are actually in use, which are called *Global*, *Serial* and *Parallel* and defined by the following equations:

$$Global \ I_T = \frac{\sum (f_i \times \bar{T}_{sk,i} - T_o)}{\sum (f_i \times \bar{Q}_{s,i})} ;$$

$$Parallel \ \frac{1}{I_T} = \sum f_i \times \left(\frac{\bar{Q}_{s,i}}{\bar{T}_{sk,i} - T_o} \right) = \sum f_i \times \frac{1}{I_{T,i}} ; \quad Serial \ I_T = \sum f_i \times \left(\frac{\bar{T}_{sk,i} - T_o}{\bar{Q}_{s,i}} \right) = \sum_i f_i \times I_{T,i}$$

where f_i represents the relationship between the surface area of segment i of the manikin, A_i , and the total surface area of the manikin A ($f_i = A_i/A$). A detailed analysis and interpretation of these three thermal insulation calculation methods can be found in Oliveira et al. (2008).

To support the present analysis 9 typical ensembles used by Portuguese workers often exposed to cold environments were tested. The measurements took place in a climate chamber (CC) at the Laboratory of Industrial Aerodynamics (LAI). The thermal manikin used in this study has 16 independent parts controlled by a computer according to the relation between dry heat losses and skin temperature of the human body for conditions close to thermal comfort (Madsen, 1976).

RESULTS

In the next paragraphs, the results obtained for the effective (I_{cle}), the basic (I_{cl}) and total (I_T) thermal insulations are presented. The detailed results of the limits of the thermal insulation values, calculated with the three methods for both postures, are presented in Table 1. For the static posture and if we restrict our comments to the I_T values, the total clothing insulation ranged between 1.64 and 3.31 clo with the *serial* method, 1.44 and 2,29 clo with the *global* method and 1.38 and 2.12 clo with the *parallel* method. For the dynamic condition, the corresponding values varied from 1.56 to 3.04 clo, from 1.32 to 1.99 clo and from 1.25 to 1.83 clo, respectively for the *serial*, *global* and *parallel* methods. As it might be expected, the static posture always leads to the highest thermal insulation values.

Considering the total thermal insulation (I_T), Table 1 shows that the mean value of the relative differences between the static and dynamic conditions [(static-dynamic) / static] is 5.5% for the *serial* method, 9.8% for the *global* and 10.9% for the *parallel* method. The corresponding values for I_{cl} are 5.0, 9.7 and 11.2% and for I_{cle} are 4.8, 7.9 and 9.5%, respectively for the *serial*, *global*

and *parallel* methods. Looking at the results obtained with the *global* method, the analysis of the highest and lowest values show that for I_{cle} the maximum and minimum reductions were 13.3 and 3.8%. For I_{cl} the maximum reduction was equal to 14.6% and the minimum was 5.6%. For I_T the decrease in insulation due to the walking movements varied from 13.4 and 7.1%.

Table 1 Calculation methods: thermal insulation limits, mean relative differences and standard deviations (SD).

Method	Thermal Insulation (clo)	Static	Dynamic	$\left(\frac{\text{static-dynamic}}{\text{static}}\right)$	
				Mean \pm SD	Range
<i>Serial</i>	I_T	1.64 — 3.31	1.56 — 3.04	5.5 ± 3.7	0.7 — 12.0
	I_{cl}	1.02 — 2.88	0.98 — 2.64	5.0 ± 4.6	0.5 — 13.4
	I_{cle}	0.83 — 2.51	0.81 — 2.32	4.8 ± 3.9	1.2 — 12.3
<i>Global</i>	I_T	1.44 — 2.29	1.32 — 1.99	9.8 ± 2.4	7.1 — 13.4
	I_{cl}	0.79 — 1.78	0.73 — 1.52	9.7 ± 3.6	5.6 — 14.6
	I_{cle}	0.64 — 1.50	0.60 — 1.30	7.9 ± 3.9	3.8 — 13.3
<i>Parallel</i>	I_T	1.38 — 2.12	1.25 — 1.83	10.9 ± 3.4	8.4 — 14.9
	I_{cl}	0.73 — 1.59	0.66 — 1.34	11.2 ± 3.9	7.2 — 17.7
	I_{cle}	0.59 — 1.34	0.54 — 1.14	9.5 ± 4.2	5.5 — 16.3

Based on the present experimental results of I_T , Figure 1 shows the linear correlations for each of the calculation methods which are valid for a walking speed of 45 steps per minute, for an air speed lower than 0.15 m/s and in the defined thermal insulation ranges.

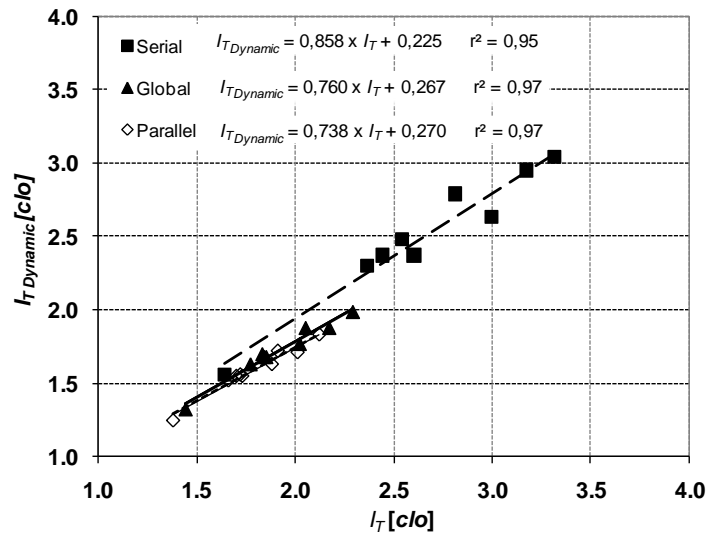


Figure 1 Relation between static (I_T) and dynamic ($I_{T\,dynamic}$) insulation values obtained in the present study.

From a complementary point of view, the present results were compared to others proposed in the literature to correct the static clothing insulation values. It should be underlined that whenever the thermal comfort regulation mode of the body parts of a thermal manikin is used, as in the present study, all the analysis must be based on the results obtained with the *global* method. Thus, in the case of the static I_T values, the equations proposed by Nilsson and Holmér (1997), Holmér et al. (1999) and Nilsson et al. (2000), are compared with the present results

showing that the mean relative error is +8.2% for Nilsson et al. (2000) and -3.8 and -5.9%, respectively for Nilsson and Holmér (1997) and Holmér et al. (1999).

$$\begin{aligned} \text{Nilsson and Holmér (1997)} \quad & \frac{I_{T_{dinamico}}}{I_T} = e^{-0.335 \times v_a - 0.214 \times w_s} \\ \text{Holmér et al. (1999)} \quad & \frac{I_{T_{dinamico}}}{I_T} = e^{0.043 - 0.398 \times v_a + 0.066 \times v_a^2 - 0.378 \times w_s + 0.094 \times w_s^2} \\ \text{Nilsson et al. (2000),} \quad & \frac{I_{T_{dinamico}}}{I_T} = e^{-0.15 \times v_a - 0.22 \times w_s} + 0.5 \end{aligned}$$

Adopting the same approach followed by Havenith and Nilsson (2004), an equation based on a wider sample was derived, gathering the results from studies similar to the present research, namely those obtained by Havenith et al. (1990) and Kim and McCullough (2000). The previous analysis was then repeated in three different steps. Figure 2 shows the present results, namely I_T values calculated with the *global* method, gathered with the ones obtained by Havenith et al. (1990) for a walking speed of 0.3 m/s. The correlation based on these results, not shown in Figure 2, is:

$$I_{T_{Dynamic}} = 0.871 \times I_T + 0.039 \quad (r^2 = 0.96)$$

If the same present results are gathered with those obtained by Kim e McCullough (2000) the correlation, also not shown in Figure 2, turns into the next equation:

$$I_{T_{Dynamic}} = 0.812 \times I_T + 0.115 \quad (r^2 = 0.84)$$

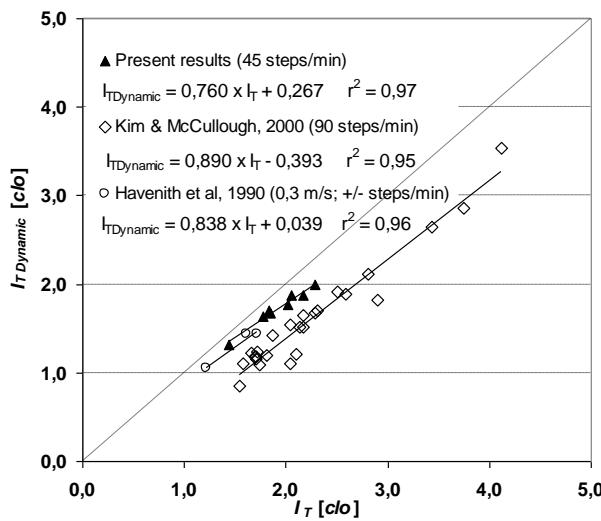


Figure 2 Relation between static (I_T) and dynamic ($I_{T_{dynamic}}$) clothing insulation values.

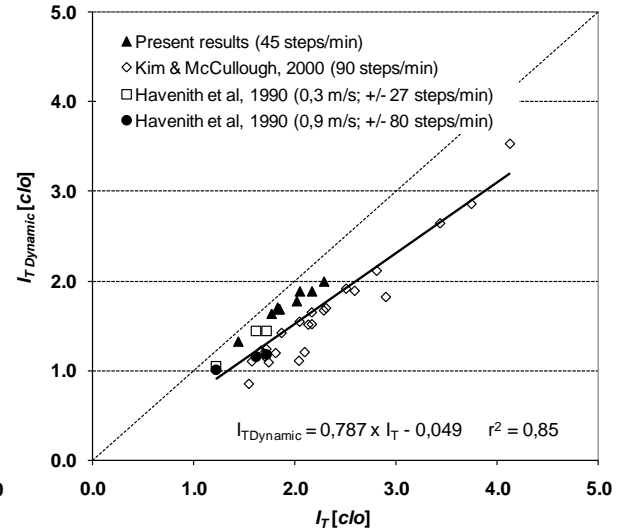


Figure 3 Relation between static (I_T) and dynamic ($I_{T_{dynamic}}$) clothing insulation values.

Finally, Figure 3 shows the correlation based on the whole sample which is:

$$I_{T_{Dynamic}} = 0.787 \times I_T - 0.049 \quad (r^2 = 0.85)$$

Figure 2 shows that for similar walking speeds, like those considered in the present work and by Havenith et al. (1990), the correlation obtained is high. On the other hand, when the walking speed differs significantly (45 steps/min in the present study and 90 steps/min used by Kim and

McCullough 2000), this effect is clearly shown. In addition, the values at higher walking speeds are more spread, showing that higher uncertainties might be expected. Therefore, whenever possible, we should always look for correlations based on experimental conditions similar to the actual, instead of equations spanning a wider range of conditions. In fact, in this case, a careful use of the correlations is highly recommended. The same conclusions, not shown here, can be outlined in the case of the I_{cl} values.

CONCLUSIONS

In the present paper thermal insulation data, obtained both in a static and dynamic condition with a manikin operating under the thermal comfort regulation mode, were gathered through measurements with cold protective ensembles. The comparison between the static and dynamic thermal insulation results has shown that the latter always corresponds to lower values, which confirms that an effective reduction in the thermal insulation should always be expected in the presence of any kind of movement. The mean relative differences [(static-dynamic) / static] for the *serial* method present the lower values, while the highest correspond to the *parallel* method. In addition, it is important to notice that the dynamic tests presents the higher mean relative differences between the calculation methods. The comparison between the experimental results obtained in this work and other correlations available in the literature has shown a good agreement and the prediction that best fits the present results is the one proposed by Nilsson and Holmér (1997). New equations are proposed to obtain dynamic insulation values from the static standardized posture, on the basis of the present results but also taking into account other studies. Finally, it is argued that in order to predict dynamic insulation values, instead of using a wide set of experimental results, preference should be given to those equations that are as close as possible to the prevailing conditions, at least as far as the walking speed is concerned.

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