THEORETICAL MAXIMA FOR CLOTHING INSULATION VALUES

M S Neale[1], W R Withey[2], C Mishan[2] and K C Parsons(')
[1] Department of Human Sciences, Loughborough University, LE11 3TU, UK
[2] Centre for Human Sciences, DERA, Farnborough, GU14 6TD, UK

INTRODUCTION

The thermal insulation of clothing (garments and ensembles) is usually measured with heated thermal manikins[1,2,3,4]. The method involves fully heating a manikin to thermal equilibrium; first nude and then clothed. Measurements of the total heat loss from the manikin at known and fixed 'skin' temperature and environmental conditions are used to evaluate clothing insulation (intrinsic, effective or total) expressed in clo units (1 clo = 0.155 $m^2.^0C.Watt^{-1}$). By definition the clo unit describes the effect of clothing in insulating the whole surface area of the human body rather than its impact on the area of the body it covers.

Inspection of documented thermal insulation values[1,3,4] reveals that clothing covering identical areas of the body often have similar measured clo values, even though the specific fabric insulation may be very different. This suggests that increasing fabric insulation beyond certain limits has little, if any, effect on measured clothing insulation, which reaches a fixed upper limit - a maximum - which is independent of clothing design, material type, clothing area factor or thickness, but which is highly dependent on the surface area of the body covered by the clothing. If such maxima do occur this could highlight possible limitations in the use of clothing insulation values measured on a fully-heated manikin.

To stimulate discussion this paper describes a theoretical study of the Nly-heated manikin method of measuring clothing insulation to confirm if maximum insulation values exist, and to determine their possible implications on the practical use of garment and ensemble insulation values.

THEORY

The theoretical approach involved the use of a simple, lumped-parameter, electrical analogy to represent the thermal insulation (clothing plus trapped air) covering the manikin. The following verification concerns intrinsic garment insulation (I_{cli}), but could equally apply to effective (I_{clu}) and total (I_T) garment insulation or similar measures performed on ensembles. Figure 1a represents the defined situation for I_{cli} - the garment's thermal insulation (eg a pair of gloves) is considered to act across the total surface area of the body; and Figure 1b the actual situation - the effect of the garment is felt over the hands alone. I, represents the thermal insulation of the air, f_{cli} the clothing area factor, A_D the DuBois surface area, A_{cov} the surface area covered by clothing, I_{clcov} the thermal insulation of the fabric (clothing plus trapped

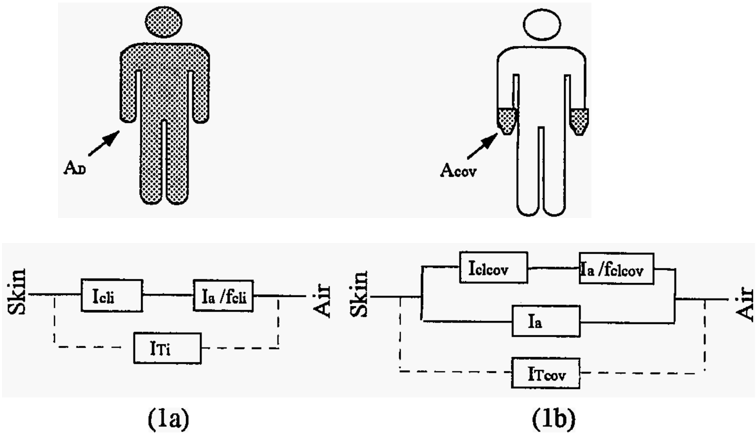

Figure 1 Electrical analogy of the fully-heated manikin method of measuring garment thermal insulation: **(1a) by detinition represents the situation in which garment insulation affects the whole surface area of the manikin; (1b) the actual situation in which the garment insulation affects only the area of the manikin it covers. Symbols are explained in the text.**

air adjacent to the skin) and f_{clcov} the clothing area factor specific **to** the area **of** the manikin that is covered. The total insulation (I_{Ti} and I_{Tcov}) of the circuits in Figure **1** are:

$$I_{Ti} = I_{cli} + \frac{I_a}{f_{cli}} \quad (1a) \qquad I_{T\,cov} = \frac{A_D}{\dfrac{A_{cov}}{I_{cl\,cov} + \dfrac{I_a}{f_{cl\,cov}}} + \dfrac{A_D - A_{cov}}{I_a}} \quad (1b)$$

Both circuits in Figure 1 represent the same thermal system with differing conceptual approaches (I_{Ti} equals I_{Tcov}). Hence combining equations 1a and 1b:

$$I_{cli} = \frac{A_D}{\dfrac{A_{cov}}{I_{cl\,cov} + \dfrac{I_a}{f_{cl\,cov}}} + \dfrac{A_D - A_{cov}}{I_a}} - \frac{I_a}{f_{cli}} \quad (2)$$

Equation **2** characterises how I_{cli} alters with changes in the area of the body covered, the insulation of the clothing with trapped and external air layers, and the clothing area factors of the whole surface area of the body and that of the surface area of the body covered. Assuming I_a = **0.62 clo**[4] and f_{cli}[5] and f_{clcov} are defined by the following equations:

$$f_{cli} = 1 + 0.31 I_{cli} \quad (3) \qquad f_{cl\,cov} = \frac{A_D}{A_{cov}}(f_{cli} - 1) + 1 \quad (4)$$

an iterative solution of equations 2, **3** and **4** can be used to investigate the characteristics of I_{cli} for variations in I_{clcov} and the percentage surface area of the body covered (Figure **2).** This shows that as I_{clcov} increases I_{cli} rises asymptotically to maxima dependent on the surface area of the body covered. When the manikin is 100 % covered with clothing a linear relationship exists between I_{cli} and I_{clcov}. The asymptotes of I_{cli} represent maximum measurable values which occur whenever the manikin is not 100 % covered. Evidence to support these findings is provided by Zhu *et al*[3] who observed similar phenomena in both theoretical and experimental studies. The values of the asymptotes are obtained by letting I_{clcov} in equation **2** approach an infinite value. Under such circumstances f_{cli} equals 1 as no heat will escape from the surface of the clothing. Hence, equation 2 reduces to:

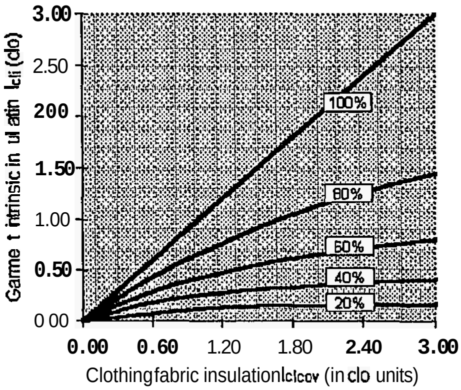

Figure 2 Relationship between garment intrinsic insulation and clothing fabric insulation for different surface areas of the heated manikin covered by clothing

$$I_{cli} = I_a\left(\frac{A_D}{A_D - A_{cov}} - 1\right) \qquad (5)$$

Equation **5** shows that maximum measurable clothing insulation values are highly dependent on the area of the manikin uncovered and on the insulation of the air layer surrounding these regions, but not on the fabric insulation of the clothing.

IMPLICATIONS OF THEORETICAL MAXIMA

The theory does not question the fully-heated manikin method for assessing the impact of clothing insulation on the wearer. However the existence of these maxima does have many implications on the practical use of the measured values. For example:

1. Clothing insulation values (clo) are used to indicate the expected impact of a garment or ensemble on heat or cold strain in the user. However it is possible for two similar garments or ensembles to have identical insulation values, but have very different effects on the local thermal responses of the wearer.
2. Measured garment insulation is often used in regression equations to estimate the expected thermal insulation of a clothing ensemble. The equations used are usually linear. However the results from this study and others[3] indicate that a non-linear relationship should be considered.

3. The maxima impose restrictions on other equations used to estimate the effect of clothing on thermal balance. For example, estimates of f_{cl} (equation 3) will reach limits which would not be present in practice.
4. Computer-based models of heat and cold strain in clothed subjects often require input of clothing insulation values to modify the thermal balance of nude subjects. Due to measured maxima the use of the clo unit to describe clothing insulation is inadequate for quantifying comprehensively the insulation of clothing for use in computer models which will make inaccurate predictions.
5. Thermal indices such as IREQ[6] predict the intrinsic clothing insulation without considering the masima or the distribution of the clothing over the body. It is therefore possible for this index to make estimations of required clothing insulations beyond limits demonstrated in our analysis.
6. I_{cli} is used to compare the results of measurements made by different researchers on the same clothing items. However, where measured clothing insulation values are close to the maxima, experimenters will obtain the Same results irrespective of the accuracy of their experimental protocols or the design or fit of the clothing on the manikin.

ALTERNATIVE METHOD

To overcome these limitations it is recommended that garment insulation should be measured on segmental thermal manikins which are heated only in those regions that are covered by clothing. The heated segment must be thermally isolated to prevent heat from travelling to adjacent, unclothed, regions of the manikin. Such measurements will not give intrinsic, effective or total insulation values as they relate only to the surface area of the manikin that is covered. However the measured values can be converted into clo units by multiplying by the fraction of the total surface area of the manikin that is covered.

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