Theoretical Analysis of Three Methods for Calculating Thermal Insulation of Clothing from Thermal Manikin

JIANHUA HUANG*

College of Textiles, Wuhan Textile University, Wuhan, Hubei 430073, China

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There are three methods for calculating thermal insulation of clothing measured with a thermal manikin, i.e. the global method, the serial method, and the parallel method. Under the condition of homogeneous clothing insulation, these three methods yield the same insulation values. If the local heat flux is uniform over the manikin body, the global and serial methods provide the same insulation value. In most cases, the serial method gives a higher insulation value than the global method. There is a possibility that the insulation value from the serial method is lower than the value from the global method. The serial method always gives higher insulation value than the parallel method. The insulation value from the parallel method is higher or lower than the value from the global method, depending on the relationship between the heat loss distribution and the surface temperatures. Under the circumstance of uniform surface temperature distribution over the manikin body, the global and parallel methods give the same insulation value. If the constant surface temperature mode is used in the manikin test, the parallel method can be used to calculate the thermal insulation of clothing. If the constant heat flux mode is used in the manikin test, the serial method can be used to calculate the thermal insulation of clothing. The global method should be used for calculating thermal insulation of clothing for all manikin control modes, especially for thermal comfort regulation mode. The global method should be chosen by clothing manufacturers for labelling their products. The serial and parallel methods provide more information with respect to the different parts of clothing.

Keywords: clothing; thermal insulation; thermal manikin

INTRODUCTION

Thermal insulation is defined as the resistance to dry heat transfer by the way of conduction, convection, and radiation (ASTM, 2005). The thermal insulation of clothing can be quantified in terms of clo unit, which was defined as the insulation of a clothing system that maintained a sitting–resting man comfortable in a normally ventilated room (0.1 m s^{-1} air velocity) at the air temperature of 21°C and the relative humidity of <50% (Gagge et al., 1941).

Since a thermal manikin is able to provide quick, realistic, accurate, and repeatable measurements, the thermal insulation of clothing can be measured with a thermal manikin (ISO 15831, 2004; ISO 9920, 2007; ASTM, 2005; EN 342, 2004). The fundamental basis for measuring thermal insulation of clothing using thermal manikin is the heat balance principle. When the system reaches the equilibrium, the heat loss is equal to the heating power into the manikin. The thermal insulation of clothing is determined based on the relationship between the power and the temperature gradient between the manikin surface and the environment.

The thermal insulation value can only be correctly understood if the test protocol is known, particularly if the thermal manikin control mode is clearly defined (Oliveira et al., 2008a). A correct method for calculating thermal insulation of clothing depends on the thermal manikin control mode. A thermal manikin can be
operated by three modes: (1) constant skin temperature; (2) constant heat flux for the body of manikin; and (3) thermal comfort regulation mode, based on the comfort equation (Melikov, 2004; Oliveira et al., 2008a,b). The constant skin temperature mode is the most commonly used.

There are three different ways for calculating the thermal insulation of the clothing, i.e. the global method, the serial method, and the parallel method. The most commonly used method is called the global method (Havenith, 2005; Oliveira et al., 2005). Later, it was adopted by the ISO 9920 [The term global method is used in ISO 9920 (2007) and we follow this. In some literature, the term parallel method is used for this, not be confused with the parallel method as described in this paper.]

Nilsson (1997) measured the total insulation of eight different clothing ensembles and found that the insulation values from the serial method were always higher than the values from the global method. Redortier (1997) measured the total insulation of a number of clothing systems and noted that the insulation values from the serial method were higher than the values from the global method and that the difference was very small between these two methods with homogeneous clothing. Anttonen (1999) sent the same clothing ensemble to seven different laboratories for the measurement of the thermal insulation with the standing and walking manikins, and the results showed that the serial method gave higher values than the global method. Holmer (2001) used wear trials to validate that the serial method overestimated the thermal insulation of two ensembles. Kuklane et al. (2004) compared the clothing insulation generated from the serial and global methods and found that the difference was up to 24% with the clothing of unevenly distributed insulation. Later, Kuklane et al. indicated that the serial method provided higher insulation values of clothing ensembles than the global method both for static and for walking conditions. This difference was larger for unequal distribution of clothing insulation (Kuklane et al., 2007). Oliveira et al. used the global, serial, and parallel methods to calculate the insulation of clothing measured with a thermal manikin operating under thermal comfort regulation mode and indicated that the relative differences of effective thermal insulation between the serial and global methods were 25.7% for the daily wear garments, 45.2% for the cold protective garments, and 38.5% for the ensembles. The relative differences between the parallel and global methods were 8.7% for the daily wear garments, 15.8% for the cold protective garments, and 10.5% for the ensembles (Oliveira et al., 2008b). Xu et al. used the parallel and serial methods to calculate the insulation values of 11 clothing ensembles measured with two thermal manikins operated under constant surface temperature mode. The results showed that the serial values were 14–38% higher than the parallel values (Xu et al., 2008). Holmer et al. studied the performance of an electrically heated vest and applied the test procedure according to the ISO 15831. When the heating was switched on, the insulation values were 1.28 and 83 clo, respectively, for the global and serial methods (Holmer et al., 2009). Recently, Wang and Lee (2010) evaluated the performance of an electrically heated vest in combination with a typical three-layer ensemble using a thermal manikin and found that the thermal insulation values from the serial method were much higher than the values from the global method due to alteration of the evenness of the insulation distribution of the ensemble. More recently, Lee et al. selected a total of 150 single garments and 38 clothing ensembles for the measurement of effective thermal insulation using a thermal manikin. The results showed that the total insulation of single garments was 16% higher in the serial method than that in the global method. For clothing ensembles, the effective thermal insulation values by the serial method were 39.2% for spring/fall wear, 62.6% for summer wear, and for winter wear 64.8% greater than the values by the global method. Lee et al. (2011) conducted human trials with 26 clothing ensembles and found that the effective thermal insulation values by the global method were systematically lower than the values from the human subjects and that the effective thermal insulation values by the serial method were lower in spring/fall and summer ensembles but greater in winter ensembles than the values obtained from the human subjects.

Most of the above-mentioned studies were based on empirical data. Although several researchers made theoretical analysis (Havenith, 2005; Xu et al., 2008), the analysis is limited. The purpose of this paper is to theoretically analyse these three methods and compare thermal insulation values computed from them. Several useful conclusions, which are theoretically valid, have been drawn.

**METHODS**

The most commonly used method, called global method or total summation (it was also called parallel method in some literatures, but it is different from the parallel method hereinafter), sums up the heat loss of all segments, area-weighted surface temperatures, and body segment areas before calculating the total insulation, which is given by (ISO 9920, 2007):
where \( I_{tg} \) = total thermal insulation of the clothing plus surface air layer by global method, \( m^2 \cdot \text{C} \cdot \text{W}^{-1} \); \( z_i \) = ratio of the surface area of segment \( i \) of the manikin to the total surface area of the manikin, \( A_i/A \); \( A_i \) = surface area of segment \( i \) of the manikin, \( m^2 \); \( T_{si} \) = local surface temperature of segment \( i \) of the manikin, \( ^\circ \text{C} \); \( T_a \) = temperature in the air flowing over the clothing, \( ^\circ \text{C} \); \( Q_i \) = local heat flux from segment \( i \) of the manikin, \( W/m^2 \); \( H_i \) = local heat loss from segment \( i \) of the manikin, \( W \).

The serial method, i.e. local summation, calculates the local thermal insulation first and the total insulation is averaged in terms of the segment area. The total insulation is formulated as follows (Anttonen, 2001; ISO 9920, 2007):

\[
I_{ts} = \sum_i \frac{A_i}{A} \times \left[ \frac{T_{si} - T_a}{H_i} \times A_i \right],
\]  

(2)

where: \( I_{ts} \) = total thermal insulation of the clothing plus surface air layer by serial method, \( m^2 \cdot \text{C} \cdot \text{W}^{-1} \).

The parallel method calculates the local heat transfer coefficient first. The total heat transfer coefficient is obtained by averaging local heat transfer coefficient in terms of the segment area. The total thermal insulation is then calculated by taking the inverse of the total heat transfer coefficient (Holmer, 2006; ISO 9920, 2007):

\[
\frac{1}{I_{tp}} = \sum_i \frac{A_i}{A} \times \left[ \frac{H_i}{T_{si} - T_a} \times A_i \right],
\]  

(3)

where \( I_{tp} \) = total thermal insulation of the clothing plus surface air layer by parallel method, \( m^2 \cdot \text{C} \cdot \text{W}^{-1} \).

The intrinsic thermal insulation of clothing is determined by subtracting off the ratio of surface air layer insulation to clothing area factor from the total insulation value:

\[
I_{cl} = I_t - \frac{I_a}{f_{cl}},
\]  

(4)

where \( I_{cl} \) = intrinsic (basic) thermal insulation of clothing, \( m^2 \cdot \text{C} \cdot \text{W}^{-1} \); \( I_t \) = total thermal insulation of the clothing plus surface air layer, \( m^2 \cdot \text{C} \cdot \text{W}^{-1} \); \( I_a \) = thermal insulation of surface air layer, \( m^2 \cdot \text{C} \cdot \text{W}^{-1} \); \( f_{cl} \) = clothing area factor.

The value of \( I_a \) is obtained by operating the manikin without clothing. The clothing area factor is an indicator of the increase in surface area for the heat loss from the clothed body to the environment. It is defined by the ratio of the clothed body surface area to the nude body surface area. This value is usually measured by taking photographs of a manikin—nude and clothed.

The effective thermal insulation of clothing is calculated by subtracting the air layer insulation from the total insulation:

\[
I_{cle} = I_t - I_a,
\]  

(5)

where \( I_{cle} \) = effective thermal insulation of clothing, \( m^2 \cdot \text{C} \cdot \text{W}^{-1} \).

For a thermal manikin, the surface area of each manikin segment is predefined. For a specific thermal manikin test in any manikin control mode, the local surface temperature of each manikin segment and the ambient air temperature are held constant when the system reaches the equilibrium. There are two cases for clothing insulation distribution: homogeneous clothing insulation and inhomogeneous clothing insulation. That is to say, the clothing insulation distribution is of our interest, and the insulation value from the global method remains unchanged. That implies that the total heat loss from the manikin is a constant as well. Let \( H \) stand for the total heat loss, i.e.:

\[
H = \sum_i H_i.
\]  

(6)

The comparison between the global and serial methods was addressed in the previous paper (Huang, 2008). Here, are the main findings from that paper:

- The global and serial methods yield the same insulation value if the clothing insulation is evenly distributed over the manikin.
- The serial method consistently gives higher insulation value than the global method if the uniform surface temperature over the manikin is achieved.
- The serial method may yield lower insulation value than the global method if the local heat loss distribution satisfies the following equations:

\[
\frac{\sqrt{m_1}}{H_1} = \frac{\sqrt{m_2}}{H_2} = \frac{\sqrt{m_3}}{H_3} = \ldots = \frac{\sqrt{m_n}}{H_n},
\]  

(7)

\[
m_i = \frac{A_i^2 \times (T_{si} - T_a)}{A},
\]  

(8)
Homogeneous clothing insulation

If homogeneous clothing insulation distribution occurs in the manikin test, the global and serial methods give the same insulation value as the insulation value of each manikin segment. Let $I$ denote this value (Huang, 2008). At this circumstance, the parallel method calculates the insulation as follows:

\[
\frac{1}{I_p} = \sum_i \frac{A_i}{A} \times \frac{1}{I} = \frac{1}{AI} \sum_i A_i, \tag{9}
\]

\[
I_p = \frac{AI}{\sum_i A_i} = I_p. \tag{10}
\]

Therefore, these three methods yield the same insulation value if the clothing insulation is evenly distributed over the manikin body. To make it more clear, supposing a thermal manikin with two segments is operated with different local heat loss distribution, the total insulation values of clothing ($I_{tg}$, $I_{ts}$, and $I_p$) from these three methods are graphed against the local heat loss ($H_{cl}$). As shown in Fig. 1, $I_{tg}$ gives a straight line since the global method produces a constant value of insulation when the total heat loss remains unchanged. When the local heat loss distribution satisfies the homogeneous clothing insulation, $I_{tg}$, $I_{ts}$, and $I_p$ are equal at Point B.

Inhomogeneous clothing insulation

Comparison between global and serial methods. Assume local heat flux is uniform over the manikin body:

\[
\frac{H_i}{A_i} = Q. \tag{11}
\]

Equation (2) becomes:

\[
I_{ts} = \sum_i \frac{A_i}{A} \times \left[ \frac{(T_{si} - T_a)}{H_i} \right] = \sum_i \frac{A_i}{A} \times \left[ \frac{(T_{si} - T_a)}{Q} \right] \tag{12}
\]

\[
= \frac{1}{AQ} \sum_i A_i \times (T_{si} - T_a).
\]

Equation (11) is rewritten to:

\[
H_i = A_i Q. \tag{13}
\]

Equation (1) becomes:

\[
I_{tg} = \sum_i A_i \times \frac{T_{si} - T_a \times A}{\sum_i H_i} = \frac{\sum_i A_i \times (T_{si} - T_a)}{\sum_i H_i}, \tag{14}
\]

\[
I_{tg} = \frac{\sum_i A_i \times (T_{si} - T_a)}{\sum_i A_i Q} = \frac{\sum_i A_i \times (T_{si} - T_a)}{Q \sum_i A_i} = \frac{\sum_i A_i \times (T_{si} - T_a)}{AQ}. \tag{15}
\]

Fig. 1. Clothing insulation from three methods with different local heat loss distribution (a thermal manikin with two segments).
Therefore, the global and serial methods yield the same insulation value if the local heat flux is uniform over the manikin body. At this circumstance, equation (15) becomes:
\[
I_{gs} = \sum A_i \frac{(T_{si} - T_a)}{Q} = \sum A_i \frac{(T_{si} - T_a)A_i}{H_i} = \sum A_i \frac{A_i}{H_i} \times I_i. \tag{16}
\]

This equation adds up the local resistances according to a serial model analogous to electrical networks.

As shown in Fig. 1, \(I_{gs}\) reaches its minimum value (Point C) when the equation (7) is satisfied (Huang, 2008). The global method and serial method provide the same insulation value if the clothing insulation is homogeneous (Point B) or the heat flux is uniform for each manikin segment (Point A). If the local heat loss distribution satisfies the condition between A and B in Fig. 1, \(I_{gs}\) is certain to be smaller than \(I_{tg}\). The more heat loss distributed to the segments with higher values of square root of \(A_i \times A_i \times (T_{rs} - T_a)\) [see equations (7) and (8)], the higher the possibility that \(I_{gs}\) is smaller than \(I_{tg}\).

\textbf{Comparison between serial and parallel methods.}

In order to compare the total insulation values from the serial and parallel methods, it is necessary to determine the partial derivative with respect to the heat loss from each segment. The partial derivative for the serial method is given by (Huang, 2008):
\[
\frac{\partial I_{gs}}{\partial H_i} = -\frac{m_i}{H_i^2} + \frac{m_n}{H_n^2}. \tag{17}
\]

For the parallel method, equation (3) can be rewritten to:
\[
I_{gp} = \frac{1}{\sum A_i \frac{H_i}{(T_{si} - T_a)}} \times \frac{A}{\sum A_i \frac{H_i}{(T_{si} - T_a)}}. \tag{18}
\]

The partial derivative is as follows:
\[
\frac{\partial I_{gp}}{\partial H_i} = -\frac{A}{\left[\sum A_i \frac{H_i}{(T_{si} - T_a)}\right]^2} \times \left(\frac{1}{T_{si} - T_a} - \frac{1}{T_{sn} - T_a}\right), \tag{19}
\]

where \(T_{sn}\) = local surface temperature at the segment \(n\), °C.

Under the condition of homogeneous clothing insulation distribution (as point B shown in Fig. 1), the partial derivatives for both methods are calculated as follows:

\textbf{Serial method:}

Substituting \(A_i(T_{rs} - T_a)/T\) for \(H_i\) in equation (17), together with equation (8), which gives:
\[
\frac{\partial I_{gs}}{\partial H_i} = -\frac{A_i^2}{A} \frac{A_i}{(T_{si} - T_a)^2} + \frac{A_i^2}{A} \frac{A_i}{(T_{sn} - T_a)^2}, \tag{20}
\]

\textbf{Parallel method:}

\[
\frac{\partial I_{gp}}{\partial H_i} = -\frac{A}{\left[\sum A_i \frac{H_i}{(T_{si} - T_a)}\right]^2} \times \left(\frac{1}{T_{si} - T_a} - \frac{1}{T_{sn} - T_a}\right), \tag{22}
\]

\[
\frac{\partial I_{gp}}{\partial H_i} = -\frac{A_i^2}{\sum A_i} \times \left(\frac{1}{T_{si} - T_a} - \frac{1}{T_{sn} - T_a}\right). \tag{23}
\]

If the uniform surface temperature occurs over the manikin body, the partial derivative with respect to the heat loss from each segment is zero for the serial and parallel methods with reference to equations (21) and (23) (see Fig. 2). If the surface temperature is not uniform, the difference (e.g., 1–2°C) among the local surface temperatures is small relative to mean surface temperature (e.g., 34°C). This difference may be caused by inadequate heating power or manual setting. As a result, the first denominator on the right side of equation (19) remains nearly unchanged no matter how the local heat loss is distributed. Consequently, the partial derivative with respect to the heat loss from each segment is nearly consistent and the parallel line in Fig. 1 is almost a straight line (actually, it is a concave line as the second partial derivative is always >0, but the curvature is negligible). Since the parallel and serial methods provide the same insulation value and the same partial derivative at Point B (homogeneous clothing insulation distribution), the parallel line can be regarded as a tangent line of the serial line at Point B. From this analysis, it is concluded that the serial method always produces greater insulation value than the parallel method.
Comparison between global and parallel methods.

Since the parallel line in Fig. 1 can be considered to be a straight line and the global line is horizontal line, the parallel and global methods yield the same insulation value only at Point B. When the local heat loss distributed to the segments satisfies the condition between the origin point and B in Fig. 1, \( I_{tp} \) is smaller than \( I_{lg} \). The more heat loss distributed to those segments with lower surface temperatures, the higher the possibility that \( I_{tp} \) is smaller than \( I_{lg} \). When the local heat loss distributed to the segments satisfies the condition beyond Point B in Fig. 1, \( I_{tp} \) is bigger than \( I_{lg} \). The more heat loss distributed to those segments with higher surface temperatures, the higher the possibility that \( I_{tp} \) is greater than \( I_{lg} \).

If the uniform surface temperature (T) occurs over the manikin body, the parallel equation becomes:

\[
\frac{1}{I_{tp}} = \frac{1}{A} \sum_i \frac{H_i}{T - T_a} = \frac{1}{A(T - T_a)} \sum_i H_i
\]

\[
= \frac{1}{A(T - T_a)} \cdot \frac{H}{A(T - T_a)} = I_{tp} = \frac{A(T - T_a)}{H}. \tag{24}
\]

The global equation becomes:

\[
I_{lg} = \frac{[(\sum_i \frac{A_i}{A} \times T_{si}) - T_a] \times A}{\sum_i H_i} = \frac{A(T - T_a)}{H}. \tag{25}
\]

Consequently, the global and parallel methods yield the same insulation value if the surface temperature is uniform over the manikin body. Both methods share the same line as shown in Fig. 2. At this circumstance, the inverse of the insulation value calculated by the global method becomes:

\[
\frac{1}{I_{lg}} = \frac{\sum_i H_i}{A(T - T_a)} = \frac{\sum_i A_i H_i}{A \sum_i (T - T_a)} = \frac{\sum_i A_i H_i}{A \sum_i I_i} \tag{27}
\]

This equation adds up the local resistances according to a parallel model analogous to electrical networks. This is the reason why the most commonly used method was called parallel method in some literatures.

DISCUSSIONS

From the above analysis, when the manikin is operated in the Mode 1—constant skin temperature, the insulation value from the parallel method is equal to the value from the global method. The parallel method can be used to calculate the thermal insulation of clothing. When the manikin is operated in the Mode 2—constant heat flux, the insulation value from the serial method is equal to the value from the global method. The serial method can be used to calculate the thermal insulation of clothing.

In reality, the skin temperatures vary at the body surface even when people are under thermal comfort condition (Olesen and Fanger, 1973; Huizenga et al., 1976).
Therefore, the uniform surface temperature distribution required in the ASTM F1291 and ISO 15831 does not simulate the real condition. When the manikin is operated in the Mode 3—thermal comfort regulation mode, the insulation value from the serial method is unrealistically higher than the value from the global method. As the global method performs an overall calculation and defines a whole body resistance, it is only valid method for calculating thermal insulation of clothing in this case. Several international standards address the measurement of thermal insulation of clothing. They give different methods for calculating total thermal insulation. If we choose any one of these three methods to calculate clothing thermal insulation, the insulation values determined by the same method are comparable. However, as the thermal insulation of clothing is an important input variable for the models that deal with cold stress and cold strain, the overestimation of the insulation value may result in error. If the high insulation value (e.g. from the serial method or the parallel method) is used for the heat balance equation, the predicted value of the heat loss of the body will be underestimated. The human body cannot maintain heat balance. This may increase the risk of adverse health effects.

Here is an example of application of thermal insulation in the model that predicts cold stress. The ISO 11079 specifies a method (IREQ model) to assess cold stress by calculating required clothing insulation (IREQ) and the duration limited exposure (DLE) (ISO 11079, 2007). Suppose the input environmental variables are listed as follows: air temperature 0°C, mean radiant temperature 0°C, relative humidity 50%, and air velocity 1 m s⁻¹. The metabolic rate is 58.2 W m⁻². These variables are input into the IREQ model. The required clothing insulation is given by 4.36 clo for low physiological strain. If the intrinsic thermal insulation of the selected clothing is less than the required clothing insulation, the exposure has to be limited to prevent progressive body cooling. The air permeability of the selected clothing (8.1 m⁻² s⁻¹) is input into the IREQ model and the duration limited exposure is determined accordingly. The intrinsic thermal insulation of the selected clothing can be obtained from the total thermal insulation, which is calculated from the global method, the serial method, and the parallel method. As shown in Table 1, the intrinsic insulation values from the serial method and the parallel method result in longer duration limited exposure than the intrinsic value from the global method. Thus, the wearers may be put into danger if they are required to work 9 h day⁻¹ in cold environments.

<p>| Table 1. Duration limited exposure from different calculation methods of clothing insulation. |
|-------------------------------------------------|-----------------|-----------------|-----------------|
| From the        | From the   | From the    |</p>
<table>
<thead>
<tr>
<th>global method</th>
<th>serial method</th>
<th>parallel method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic thermal insulation (clo)</td>
<td>2.67</td>
<td>3.16</td>
</tr>
<tr>
<td>Duration limited exposure (h)</td>
<td>5.3</td>
<td>9.1</td>
</tr>
</tbody>
</table>

Therefore, the global method represents more accurately the thermal protection actually provided by clothing and can be used for calculating thermal insulation of clothing for all manikin control modes. The thermal insulation calculated by incorrect methods will be misleading.

**CONCLUSIONS**

This study aims to theoretically analyse these three methods for calculating thermal insulation of clothing from thermal manikin test. Which method is used for the computation of clothing insulation depends upon the manikin control modes. The parallel method can be used to calculate the thermal insulation of clothing when the constant skin temperature mode is used. The serial method can be used to calculate the thermal insulation of clothing when the constant heat flux mode is used. The global method can be used for calculating thermal insulation of clothing for all manikin control modes. When the manikin is operated in the thermal comfort regulation mode, the global method is only valid one to calculate the insulation value of clothing.

The thermal insulation value of clothing represents quantitative evaluation of how good thermal barrier the clothing provides the user. In order to boost sales, the clothing manufacturers often label their products with thermal insulation values. However, the discrepancy between these three calculation methods is high, particularly for cold protective ensembles. The global method should be used in order to prevent clothing manufacturers to manipulate insulation distribution to obtain higher insulation values. The clothing manufacturers are supposed to choose the global insulation for labelling their products.

The local insulation of clothing would be useful in the applications of segmented thermal models, which require descriptions of local/regional clothing insulation (Huijzena et al., 2001; Zhang et al., 2010a,b). The serial and parallel methods are more useful in regard to the local insulation values of clothing, which provides important information about the critical segments that can be used at the
design stage of protective ensembles. This contributes to identify the critical body parts and redesign the ensembles to acquire appropriate insulation distribution over the whole body.

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