Clothing heat exchange models for research and application

CLOTHING HEAT EXCHANGE MODELS FOR RESEARCH AND APPLICATION

George Havenith

Environmental Ergonomics Research Group, dept. Human Sciences, Loughborough, UK
* corresponding author g.havenith@lboro.ac.uk

Introduction

The regulated exchange of heat from the human body to the environment is essential in human survival. This exchange is adjusted by our physiological response mechanisms. We are able to sweat profusely to cool the body in exercise and heat exposure, and are able to fine-tune our body temperatures in moderate environments through variations in skin circulation.

In slightly cool environments, we reduce blood flow to our extremities and skin and use our fat layer insulation to conserve central body temperature. We can increase our heat production by shivering and can create a small insulating air layer around our skin by pilo-erection. However, when temperature goes down further, we cannot sustain our body temperature in the long run without behavioural adjustments that include putting on clothing or using heated dwellings. In this context, clothing has allowed mankind to expand its habitat around the world and has had a positive influence on its development.

Today, clothing is worn for various reasons. Apart from its functional aspects (insulation, protection), it has a strong cultural and social aspect as well. The latter are on occasion counterproductive in terms of the first. A business suit for instance is hardly functional in a tropical climate, nor is a ladies evening dress in a cold environment. Also, when the function of the clothing is not only protection against heat or cold, as e.g. is the case with chemical protective clothing, the barriers introduced in the clothing to achieve the required protection can cause a conflict between the protective function of the clothing and the thermal functioning of the body. These conflicts can lead to discomfort, but also to physical strain and in extreme cases can put the person at risk from heat or cold injury or illness.

In order to understand these relations and conflicts, we need to study not only what happens in terms of thermoregulation in the body, but also how heat is transferred from skin to environment. For heat loss from the body, between skin and environment, several pathways are available. For each pathway the amount of transferred heat is dependent on the driving force (e.g. temperature or vapour pressure gradient), the body surface area involved and the resistance to that heat flow (e.g. clothing insulation):

$$Heat\ \ Loss = \frac{gradient \cdot surface\ area}{resistance} \qquad \textbf{<1>}$$

Usually the descriptions of the heat exchanges are confined to conduction, convection, radiation and evaporation. A minor role is normally taken by conduction, which is usually only referred to when people are in contact with solids. More important for heat loss is convection. When air flows along the skin, it is usually cooler than the skin. Heat will therefore be transferred from the skin to the air around it. Also heat transfer through electro-magnetic radiation can be substantial. When there is a difference between the body's surface temperature and the temperature of the surfaces in the environment, heat will be exchanged by radiation. Finally, the body possesses another avenue for heat loss, which is heat loss by evaporation. Due to the body's ability to sweat, moisture appearing on the skin can evaporate, with which large amounts of heat can be dissipated from the body.

In most calculations and description of these heat losses, clothing is represented as a resistance to dry heat loss and as an evaporative heat resistance. However realistically many more parameters are required to fully describe clothing heat transfer, leading to rather complex descriptions or models. Both approaches will be discussed here.

Detailed models

In order to describe the heat transfer through clothing fully one needs to include a number of processes. If we assume clothing built up of a number of textile layers with a still air layer on their surfaces, and possibly mobile air layers on top of those, the following heat transfer processes may take place:

Dry:
Conduction: dry heat is transferred by conduction through the still air layers that are found on the surface of the textile layers, as well as through the air within the textile layers and through the textile fibres. Conductivity of textile fibres is much higher than that of still air, indicating the importance of trapped air within garments to the conductive heat loss (Table 1).
Convection: where the air is not held still by textile fibres, and is able to move due to natural convection (rising of warmed air) or is forced to move by forced convection (wind, body movements creating a bellows effect) heat will be transported with the air moved defined by its enthalpy.

Radiation: heat can be transported between the environment and the clothing surface by electro-magnetic radiation. This also occurs between clothing layers, and finally radiant heat transport can take place between the fibres within a textile, through the entrapped air. The more fibres, the less radiant transfer, though an optimum for overall conductivity of a textile is based on the balance between radiation and convection (denser → less radiation but more conduction through the fibre content).

Wet:
The water vapour molecules of evaporated sweat, having 'absorbed' around 2430 $J.g^{-1}$ of heat at the skin, can be transported to the environment in various ways:

Table 1: Thermal conductivity of various textile fibres (1)

Material	$W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$
Wool	0.19
Silk	0.21
Linen	0.29
Cotton	0.29
Polyamide	0.23
Polyester	0.18
Polyacryl	0.18
air	0.026

Diffusion: the movement of water vapour molecules through still air and textiles allows moisture to be lost from the skin and keeps the microclimate dry enough to allow more sweat evaporation.
Convection: similar to dry heat loss by convection, moving air will take with it the moisture contained in the microclimate, which can then be replaced by fresh air if the convective stream actually leaves the garment (ventilation). If not, it will have an equilibrating effect on local microclimate conditions.
Absorption (adsorption): water vapour travelling through textiles may be absorbed by the textile fibre. All materials, when allowed to absorb vapour until an equilibrium is reached, have characteristic absorption levels (expressed as regain), which increase with relative humidity and are typically higher for natural versus man-made fibres. With this absorption heat is released in the textile, composed of the heat of condensation and the heat of swelling, raising the local temperature. If liquid is absorbed, only the heat of swelling is released.

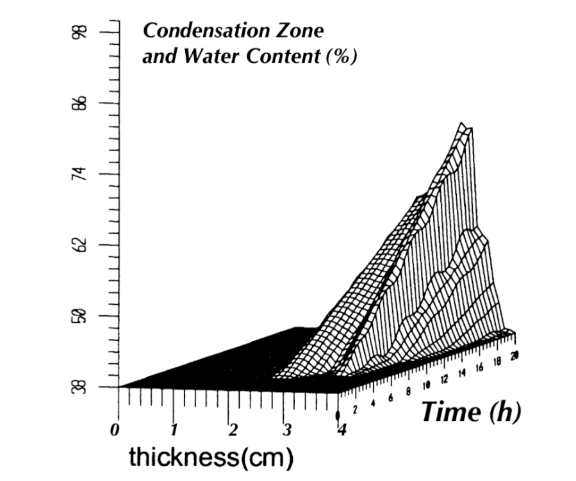


Fig. 1 Example of finite element modeling calculation showing distribution of condensed water in a wool batting (adapted from (2)).

Desorption: Any water bound to the textile fibres may be released as vapour again and take with it the heat of swelling plus the heat of evaporation, i.e. the reversal of absorption. This will reduce the local temperature.
Condensation: In most situations a temperature gradient as well as a water vapour gradient is present from the skin to the environment. This drives the transport of heat and moisture. These two interact however, as with reducing temperature along this temperature gradient, also the dewpoint of the local air is reduced. This dewpoint limits the water vapour concentration at that location, and if that is exceeded, condensation of moisture with a release of heat will occur at that point, raising the local temperature.

Models that study heat transfer processes in clothing in detail will need to incorporate these factors. Various approaches are possible with numerical or analytical solutions. Good examples are the models developed by the groups around Jones,

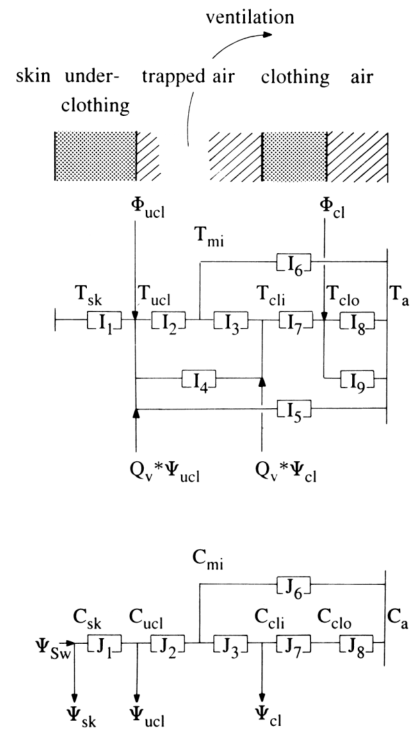


Figure 2, four layer clothing model and related heat and vapour resistance network (6)

Li, Fan, Ghali, Ghaddar and Lotens (2, 3, 4, 5, 6). Much of this work is based on Henri's work from 1939 (7).

Many of these modellers revert to finite element modelling for their simulations, as the analytical solutions are almost impossible without simplifications (2). In essence this divides all clothing and air layers into a matrix of elements and heat and moisture transport etc. between all adjacent elements is calculated in short time increments. Given the complexity of even this exercise, most of these models are only one dimensional in space. However they do allow in depth analyses of all relevant processes over time in a cross section of the clothing (Figure 1).

These models are mainly used by material and textile engineers for basic research. They have not found wide acceptance in the research area of environmental ergonomics due to their mathematical complexity, which makes them difficult to work with for a major part of that research community.

The problems with this complexity, and the debate whether this level of complexity is needed for most applications of these models has led some researchers to simplify these models. E.g. by representing clothing layers not as multinode structures with interaction of heat and moisture transfer in each node but by describing them with fixed values for heat and vapour resistance and reducing the number of nodes dramatically. This was the approach taken by Lotens (6). A schematic drawing of Lotens' model is provided in Figure 2. He has reduced the clothing to a representation by 4 layers, underclothing (including the skin air layer), microclimate between underclothing and outer clothing, the actual outer clothing layer and the outer surface air layer. He did include radiation, convection, diffusion and ventilation and only within three nodes he allows interaction of heat and moisture transfer. Farnworth (8) took the simplification one step further using a simple description with fixed values for heat and vapour resistance. The advantage is a drastic simplification; the disadvantage is that processes, like pumping effects and ventilation, are neglected as well.

Lumped models

In the area of environmental ergonomics there is a large group of practitioners and researchers for whom the detailed analysis of heat transfer processes in clothing is not essential. Rather they are interested in the overall influence the clothing has on the wearer. Examples can be found in the areas of heat (9) or cold stress (10) prediction, or in the area of indoor climate research looking at thermal comfort (11). For these applications the complex models are not practical, as with their large numbers of parameters that can be set and changed, understanding of the implications is soon lost. For these applications a calculation of the overall human heat balance is the main basis for the analysis, and hence these can work with very simplistic models of clothing heat transfer, which in some applications goes down to representing the clothing as a single heat resistance with all other parameters derived from this (e.g. (11)). This approach has led to the development of ISO 9920 (12) and ISO 15831 (13), describing the clothing as a single heat and a vapour resistance, combined with those of the surface air layer (Fig. 3).

This allows the calculation of heat loss from the skin for steady state situations, but does not allow study or calculations of transients, changes in insulation due to moisture accumulation, increased ventilation etc. This standard has become tremendously popular with practitioners (climate assessment; building HVAC designers) as it provided examples of the heat resistance values of many different clothing ensembles, which could be used in calculations without the need to measure the actual insulation worn. The standard provided extensive data on heat resistance of clothing and limited data on vapour resistance, obtained on thermal manikins. The latter was usually treated as having a direct relation with heat resistance (Lewis relation) allowing its deduction from it. Especially for comfort conditions this approach appeared to be satisfactory.

For other work conditions, where more stressful conditions were present this approach was found to be overly simplistic. It did not take proper account of increased air speeds, radiation effects on specialised clothing, rain protective clothing etc. etc. Some of these factors are now addressed in the revision of ISO 9920, expected to be published at the end of 2005.

Given the popularity of this approach, the following sections will look into this in more detail and identify some areas that are currently under discussion or require more attention in future research.

The f_{cl} factor

The classic equation for calculation the clothing insulation that relates to Figure 3 is:

$$I_T = I_{cl} + \frac{I_a}{f_{cl}} \qquad \textbf{<2>}$$

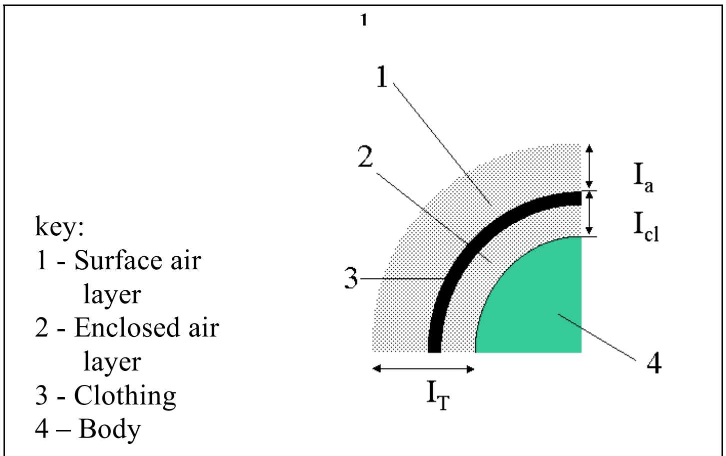
with:

I_T = Total Insulation provided by clothing and surface air layer; I_{cl} = Intrinsic clothing insulation, I_a =surface air layer insulation, and f_{cl} = clothing area factor; ratio of the outer surface area of the clothed body to the surface area of the nude body

While I_{cl} and I_a can be measured or looked up in tables, f_{cl} has to be determined by photographic or body scanning techniques (14). But as this is highly labour intensive, f_{cl} is usually calculated using one of various regression equations proposed in literature. (15). During the revision phases of ISO 9920 and ISO 7730, these equations were criticised for predicting too large f_{cl} factors, and new research initiated to look into this. A problem with the regression equations available is that they were based on only a weak relation between f_{cl} and I_{cl}, and this within a domain of I_{cl} of 0.2 to 1.7 clo only (aiming at office clothing and light to medium workwear). So they were not designed for cold weather clothing and a large error for individual ensembles can be expected. However, when the sensitivity of the calculation of I_T for different f_{cl} calculations is investigated, it can be demonstrated that the impact of an error in f_{cl} is small. If I_T values in relation to I_{cl} values for the current f_{cl} prediction in ISO 9920 (f_{cl} =1+0.28 I_{cl}), are compared to those for two equations with largely deviating coefficients (0.13 and 0.43 instead of 0.28; much larger than any found in literature), it can be seen that even for such extreme deviations, the final impact on the insulation calculation is small. Difference are all less than 4.5%, even for such extreme f_{cl} changes.

Radiation

Data collected in ISO 9920, are all based on measurements where no added radiant load is present, so ambient temperature (T_a) = mean radient temperature (T_{mrt}) = operative temperature (T_o). In case radiation is present, the representation of insulations of Figure 3 only provided limited opportunity to incorporate this in the calculations. If the clothing's outer surface reflectivity is known, and one assumes that only reflection or absorption of radiation takes place at the clothing surface (i.e. no penetration/transmission), it is possible to calculate convective and radiant heat transfer from the clothing surface to the environment correctly, with all heat transfer inside the clothing assumed to have a fixed radiant component that does not change in radiant exposures. So, though this allows a first order approximation of radiation effects, it is not a complete model for this



2. Figure 3 — Schematic representation of insulation definitions. I_{cl} = Intrinsic clothing insulation; I_a = outer surface air layer insulation, I_T =total insulation.

purpose as in radiation exposures also radiant fluxes inside the clothing or interior microclimate are bound to change. In various ISO standards for the assessment of heat stress, such conditions, and/or specialised clothing, are deemed to be outside of the scope for this reason.

Currently a European Union Research Project called 'THERMPROTECT', dealing with these issues is under way, and first results will be discussed at this conference.

Air speed/pumping effects

Apart from not including radiation issues, the model used for insulation in ISO 9920 also does not intrinsically contain effects of body movement or wind penetration, which both can cause ventilation of the clothing microclimate with outside air. As the insulation from skin to clothing surface is treated as one fixed value, no extra pathway for ventilation is included (see Fig. 2 for model that does include this). These wind penetration and pumping effects can have substantial effects on the insulation provided by the clothing, however, with reductions for light clothing going towards 40% of total insulation (16). Rather than making the model (Fig. 3) more complex, the standardisation group dealing with ISO 9920 has now chosen to provide correction equations to users of the standard, that allow them to use the static values from the ISO 9920 tables and convert these to dynamic value for activity and wind (Fig 4, [17, 18]).

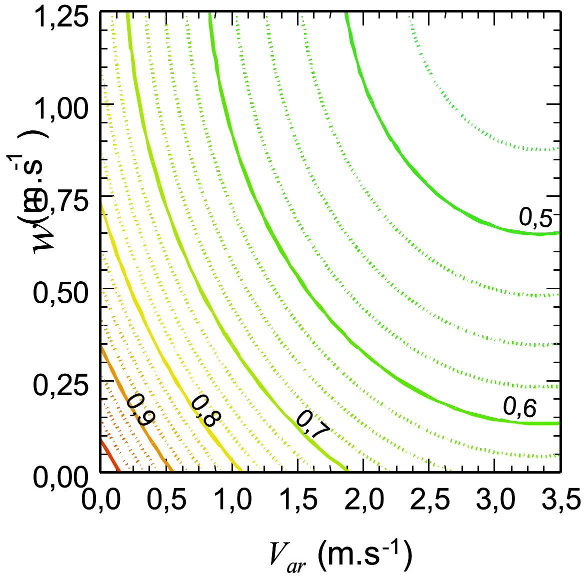


Figure 4 — Correction factor ($I_{T,r} / I_T$) for dressed subjects; validity up to 1,2 m·s^{-1} walking speed (w) and 3,5 m·s^{-1} relative wind speed (v_{ar}) (source[18]).

Different experimental and calculation methods for manikin data

The various standards describing the measurement of clothing insulation with a thermal manikin and those providing example data for various clothing ensembles have been developed with different applications in mind. While ISO 9920 and related manikin based data tables have been initiated with human heat balance analysis as goal (application of ISO thermal comfort and climatic stress standards; initially focussed on office worker's clothing and from there has expanded to workwear), other standards, like the cold weather clothing standard (EN342, (20)) and the manikin standard EN ISO 15831 (13), have been developed from the clothing testing, evaluation and certification viewpoint. This has caused a difference in methods for the manikin measurement of clothing insulation, most notably a difference in the wind speed used. While the data in ISO 9920 are almost exclusively obtained at wind speeds below 0.2 m.s^{-1} (most around 0.1 m.s^{-1}), the other standards work at 0.4 m.s^{-1}. Though the difference in wind speed seems small this can have a substantial effect on the insulation measurement of up to 12% for light clothing, less for heavier clothing. Hence this should be accounted for when getting data from different sources.

Apart from the issue with reference wind speeds mentioned above, another problem has been introduced in the interpretation of insulation data due to development of different standards in parallel. This issue relates to the calculation of the overall heat resistance provided by clothing from the data obtained from a multizone manikin. In the simple case of a single zone manikin, the insulation is simply calculated by dividing the temperature gradient between skin and environment by the total heat input to the manikin. This is also possible for multizone manikins, but another method has been proposed as well (21, 13)

Three calculation methods are in use:

1 – The general formula for defining whole body resistance, best fitting the insulation definition of ISO 9920:

$$with\ \alpha_{\mathrm{i}} = \frac{surface\ area\ of\ segment\ i}{total\ surfacearea\ of\ manikin}$$

$\overline{t_{sk}}$ = average skin temperature

t_i = temperature of segment *i*

t_a = ambient temperature (if mean radient temperature differes from ambient, replace by operative temperature)

H_i = heat loss of segment *i*

$$I_{\mathrm{T}} = \frac{\overline{t_{sk}} - t_a}{H_{sk}} = \frac{\sum \alpha_i . t_i - t_a}{\sum(\alpha_i . H_i)} = \frac{\sum \alpha_i .(t_i - t_a)}{\sum(\alpha_i . H_i)} \qquad \textbf{<3>}$$

2 – If one makes the assumption that skin temperature is uniform over the body, i.e. $t_i = t_{sk}$ = constant, then equation <3> becomes :

$$I_{\mathrm{T}} = \frac{\overline{t}_{\mathrm{sk}} - t_a}{\sum(\alpha_i . H_i)} \qquad \textbf{<4>}$$

or:

$$\frac{1}{I_{\mathrm{T}}} = \frac{\sum \alpha_i . H_i}{\overline{t}_{\mathrm{sk}} - t_a} = \sum \alpha_i . \left(\frac{H_i}{\overline{t}_{\mathrm{sk}} - t_a} \right) = \sum \alpha_i . \frac{1}{I_{\mathrm{T},i}} \qquad \textbf{<5>}$$

This is adding up resistance according to a **parallel model**, used in ASTM F1291, ISO9920 and ISO/CD15831 (19, 20, 13).

3 – If the assumption is made that local heat flux is uniform over the body, i.e. $H_i = H_{sk}$ = constant, then equation <3> becomes:

$$I_{\mathrm{T}} = \frac{\sum \alpha_{\mathrm{i}} .(t_i - t_a)}{\sum(\alpha_{\mathrm{i}} . H_i)} = \frac{\sum \alpha_{\mathrm{i}} .(t_i - t_a)}{H_{sk}} = \sum \alpha_{\mathrm{i}} . \frac{t_i - t_a}{H_{sk}} = \sum \alpha_{\mathrm{i}} . I_{\mathrm{T,i}} \qquad \textbf{<6>}$$

This equation is adding up resistances according to a **serial model**, used in ENV342, EN13537, and ISO15831 (20, 21, 13).

In practice most measurements of clothing or sleeping bag insulation are made with constant skin temperature (EN ISO 15831) as this takes a lot less time. Mostly this is done with equal skin temperatures all over the body pointing to the parallel method, but even if temperature of hands and feet is lowered as suggested for some applications, it would be very seldom that the condition of uniform heat loss is approached. If this assumption is not met however, the calculation of the serial model becomes highly error prone. With uneven distribution of insulation (e.g. nude hands and head in cold weather clothing), the serial method will produce much higher total insulation values than the parallel method and, if used in total body heat balance models, the serial method based insulation values will give unrealistic results in such cases. E.g. if we would highly insulate a single body compartment it is possible to drive up the local insulation dramatically. In the serial model this will than also push up overall insulation proportionally. This is illustrated in Figure 5. Putting on several pairs of socks and gloves on top of each other causes the large change in total insulation with the serial method on the left of both graphs. In reality total body heat loss will only change minimally. If we would use the whole body serial value to calculate backwards how much heat input the manikin required, a large discrepancy with the actually observed value would be observed. For the parallel method this is not the case.

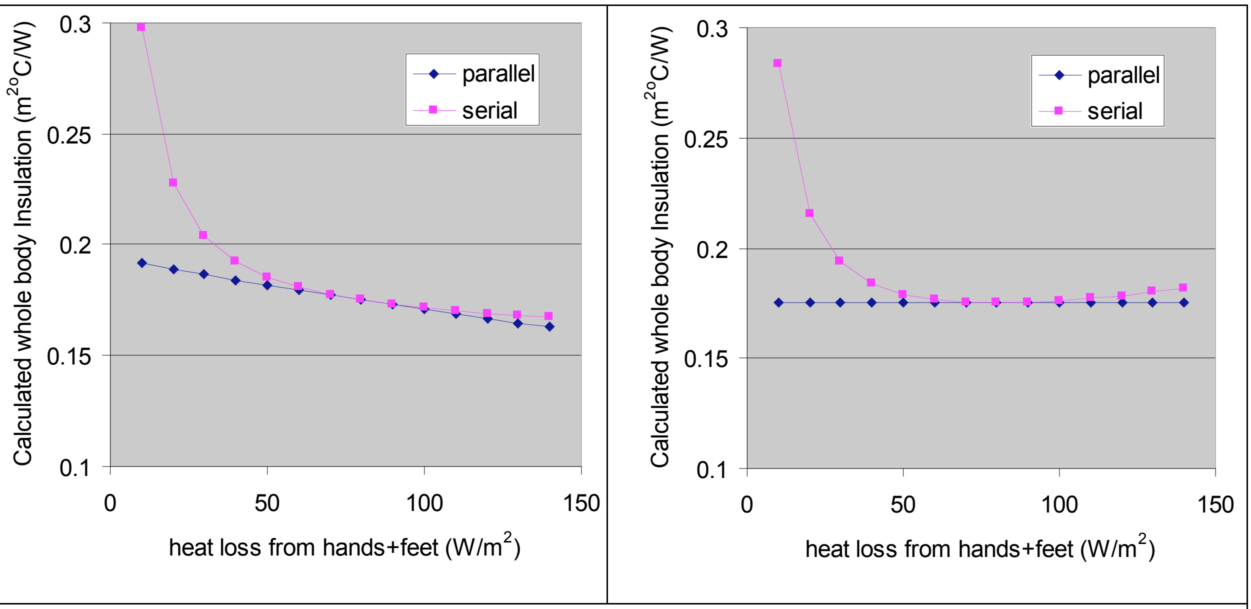


Fig. 5, total body insulation calculated with both the parallel and the serial model in light clothing. Left: heat loss from hands and feet (i.e. the insulation) is varied while the heat loss from other zones is constant at 80 W/m^2. Right: a fixed total body heat loss is assumed of 80 W/m^2, with a varying insulation on hands and feet.

One requirement for the parallel method is however that the ensemble is representative for the use situation. Leaving off gloves from a highly insulative ensemble would have a huge effect (as it would in real life), which cause could be easy overlooked in the application of the data.

With the development of manikins with more and hence smaller zones, this issue becomes more relevant, as a malfunction of a single, small, zone would offset the result of the serial calculation heavily with small impact on the parallel one.

Conclusions

A choice of clothing models is available for simulations and estimations of clothing heat and vapour transfer. For the study of the actual heat and moisture transfer in textiles, models tend to be multinode and mathematically complex, creating a barrier to their widespread use. Several attempts to simplify the approach have been successful for use in practical applications. The most simplified model, as used in ISO 9920, has received widespread use in climate assessment and clothing assessment and certification. However, the simplicity comes at a cost of requiring a number of empirical correction factors to be used to account for effects of movement, wind and radiation. Also development of different methods for calculation of insulation values based on this model has introduced a source for confusion.

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