Heat balance when wearing protective clothing

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Summary

This issue of the Annals of occupational Hygiene is dedicated to the topic of heat stress evaluation. For this evaluation, several evaluation programs and international standards are available. In order to understand the reasoning and underlying theory behind these programs and standards, a basic knowledge of heat exchange processes between workers and their environment is needed. This paper provides an overview of the relevant heat exchange processes, and defines the relevant parameters (air and radiant temperature, humidity, wind speed, metabolic heat production and clothing insulation). Further it presents in more detail the relation between clothing material properties and properties of clothing ensembles made from those materials. The effects of clothing design, clothing fit, and clothing air permeability are discussed, and finally an overview of methods for the determination of clothing heat and vapour resistance is given.

1 Introduction

Performing work in a warm or hot environment is in general more stressful for the worker than performing similar work in a neutral environment. The physical load, which accompanies heat exposure, can increase the risk of danger to the workers safety and health. The need to wear (protective) clothing in such conditions may lead to intolerable heat strain, as the clothing will have a detrimental effect on the workers ability to lose heat to the environment. Protective clothing therefore causes a downward shift in the temperature level at which heat stress occurs. Experience gathered in the military, for infantry men wearing chemical protective garments has shown that in medium heavy to heavy work, the temperature threshold above which heat stress is observed falls well below 20°C. Even people working in the cold, as e.g. in cold stores may experience heat stress due to clothing. There, clothing is usually geared towards the coldest environment. This means that its insulation is far too high when the workers temporarily leave the cold workplaces or when they for some reason have to increase their work rate unexpectedly, e.g. when equipment brakes down and forces them to do physically demanding repair work in the cold.

In this paper, the causes for this effect of protective clothing will be examined and explained. Before starting to discuss the effects of clothing however, it is first necessary to discuss the way the body regulates its temperature without interference of clothing.

2 Heat Balance

Normally the body temperature is about 37 °C. This value is achieved by balancing the amounts of heat produced in the body with the amounts lost (Fig. 1).

Heat production is determined by metabolic activity. When at rest, this is the amount needed for the body's basic functions, as e.g. respiration and heart function to provide body cells with oxygen and nutrients. When working however, the need of the active muscles for oxygen and nutrients increases, and the metabolic activity increases. When the muscles burn these nutrients for mechanical activity, part of the energy they contain is liberated outside the body as *external work*, but most of it is released in the muscle as heat. The ratio between this external work and the energy consumed is called the *efficiency* with which the body performs the work. This process is similar to what happens in a car engine. The minor part of the fuel's energy is actually effective in the car's propulsion, and the mayor part is liberated as waste heat. The body, as the car engine, needs to get rid of this heat; otherwise it will warm up to lethal levels.

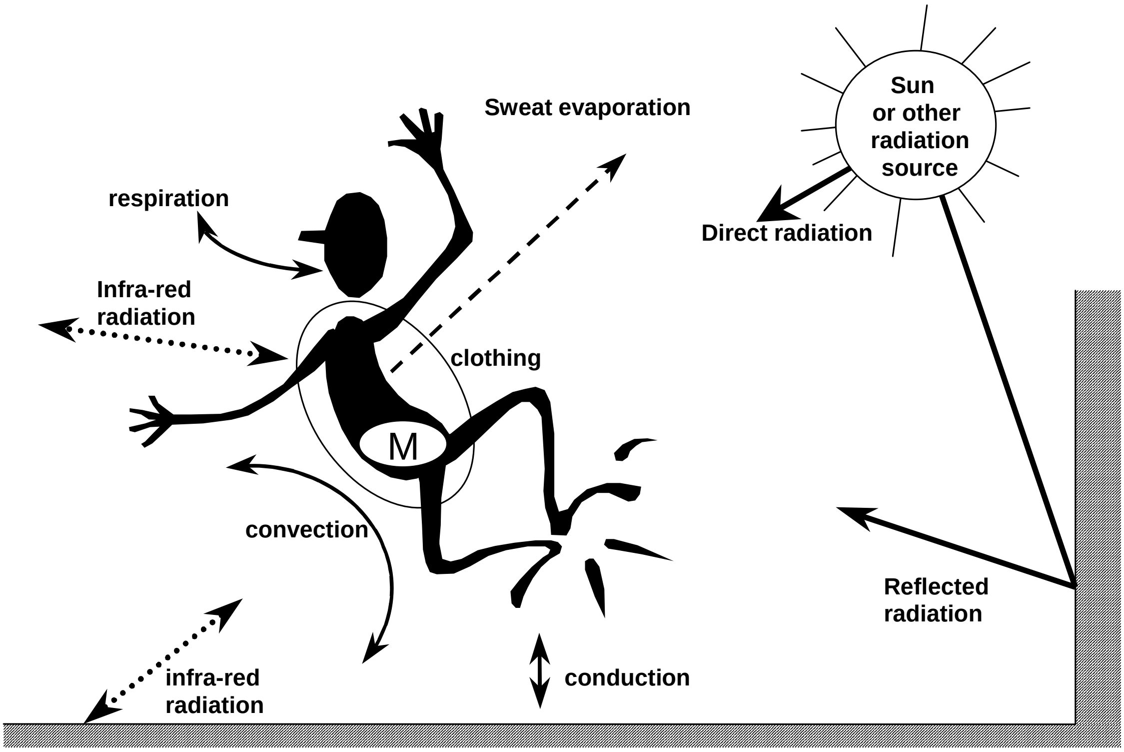

Figure 1, schematic representation of the pathways for heat loss from the body. M = metabolic heat production.

For most tasks, as e.g. walking on a level, the value for the efficiency (in its physics definition) is close to zero. Only the heat released by friction of shoes etc. is released outside the body, whereas all other energy used by the muscles ends up as heat within the body.

For *heat loss* from the body, several pathways are available. A minor role is taken by *conduction*. Only for people working in water, in special gas mixtures (prolonged deep-sea dives), handling cold products or in supine positions, conductivity becomes a relevant factor.

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 are dissipated from the body.

Apart from convective and evaporative heat loss from the skin, these types of heat loss also take place from the lungs by *respiration*, as inspired air is usually cooler and dryer than the lung's internal surface. By warming and moisturising the inspired air, the body loses an amount of heat with the expired air, which can be up to 10% of the total heat production.

For body temperature to be stable, heat losses need to balance heat production. If they do not, the body heat content will change, causing body temperature to rise or fall. This balance can be written as:

Store = Heat Production – Heat Loss = Metabolic Rate – (Conduction + Radiation + Convection + Evaporation +

Thus if heat production by metabolic rate is higher than the sum of all heat losses, Store will be positive, which means body heat content increases and body temperature rises. If store is negative, more heat is lost than produced. The body cools.
It should be noted that several of the "heat loss" components might in special circumstances (e.g. ambient temperature higher than skin temperature) actually cause a heat gain, as discussed earlier.

3 Relevant parameters in heat exchange

The capacity of the body to retain heat or to lose heat to the environment is strongly dependent on a number of external parameters:

3.1 temperature

The higher the air temperature, the less heat the body can lose by convection, conduction and radiation. If the temperature of the environment increases above skin temperature, the body will actually gain heat from the environment instead of losing heat to it. There are three relevant temperatures:

- *Air temperature*. This determines the extent of convective heat loss (heating of environmental air flowing along the skin or entering the lungs) from the skin to the environment, or vice versa if the air temperature exceeds skin temperature.
- *Radiant temperature*. This value, which one may interpret as the mean temperature of all walls and objects in the space where one resides, determines the extent to which radiant heat is exchanged between skin and environment. In area's with hot objects, as in steel mills, or in work in the sun, the radiant temperature can easily

exceed skin temperature and results in radiant heat transfer from the environment to the skin.

- *Surface temperature*. Apart from risks for skin burns or pain (surface temperature above 45°C), the temperature of surfaces in contact with the body determines conductive heat exchange. Apart from its temperature, the surface's properties, as e.g. conductivity, specific heat and heat capacity, are also relevant for conductive heat exchange.

3.2 air humidity

The amount of moisture present in the environment's air (the moisture concentration) determines whether moisture (sweat) in vapour form flows from the skin to the environment or vice versa. In general the moisture concentration at the skin will be higher than in the environment, making evaporative heat loss from the skin possible. As mentioned earlier, in the heat evaporation of sweat is the most important avenue for the body to dissipate its surplus heat. Therefore situations where the gradient is reversed (higher moisture concentration in environment than on skin) are extremely stressful and allow only for short exposures. It should be noted that the moisture concentration, not the relative humidity is the determining factor. Air that has a relative humidity of 100% can contain different amounts of moisture, depending on its temperature. The higher the temperature, the higher the moisture content at equal relative humidities. When the air temperature is lower than the skin temperature, sweat will always be able to evaporate from the skin, even at 100% relative humidity.

3.3 wind speed

The magnitude of air movement effects both convective and evaporative heat losses. For both avenues, heat exchange increases with increasing wind speed. Thus in a cool environment the body cools faster in the presence of wind, in an extremely hot, humid environment, it will heat up faster.

3.4 clothing insulation

Clothing functions as a resistance to heat and moisture transfer between skin and environment. In this way it can protect against extreme heat and cold, but at the same time it hampers the loss of superfluous heat during physical effort. E.g. if one has to perform hard work in cold weather clothing, heat will accumulate fast in the body due to the high resistance of the clothing for both heat and vapour transport.

The way in which clothing affects heat and vapour transport will be dealt with in more detail below.

4 Clothing

Clothing acts as a barrier for heat and for vapour transport between the skin and the environment. This barrier is formed both by the clothing materials themselves and by the air they enclose and the still air that is bound to its outer surfaces.

equations showing effect of clothing heat and vapour resistance on heat loss :

$$Dry\ Heat\ Loss = \frac{(t_{sk} - t_a)}{I_{tot}}$$

$$with: t_{sk} = skin\ temperature$$

$$t_a = air\ temperature$$

$$I_{tot} = clothing\ insulation,\ including\ air\ layers$$

$$Evaporative\ Heat\ Loss = \frac{(p_{sk} - p_a)}{R_e}$$

$$with: p_{sk} = skin\ vapour\ pressure$$

$$p_a = air\ vapour\ pressure$$

$$R_e = clothing\ vapour\ resistance,\ including\ air\ layers$$

4.1 clothing materials

Heat transfer through clothing materials consists mainly of conduction and radiation. For most clothing materials, the volume of air enclosed is far greater than the volume of the fibres. Therefore the insulation is very much dependent on the thickness of the material (i.e. the enclosed air layer) and less on the fibre type. The fibres mainly influence the amount of radiative heat transfer, as they reflect, absorb and re-emit radiation. That this effect is of minor importance relative to the thickness (except for special reflective clothing) can be seen in fig. 2, where the insulation of a range of different clothing materials is presented in relation to their thickness.

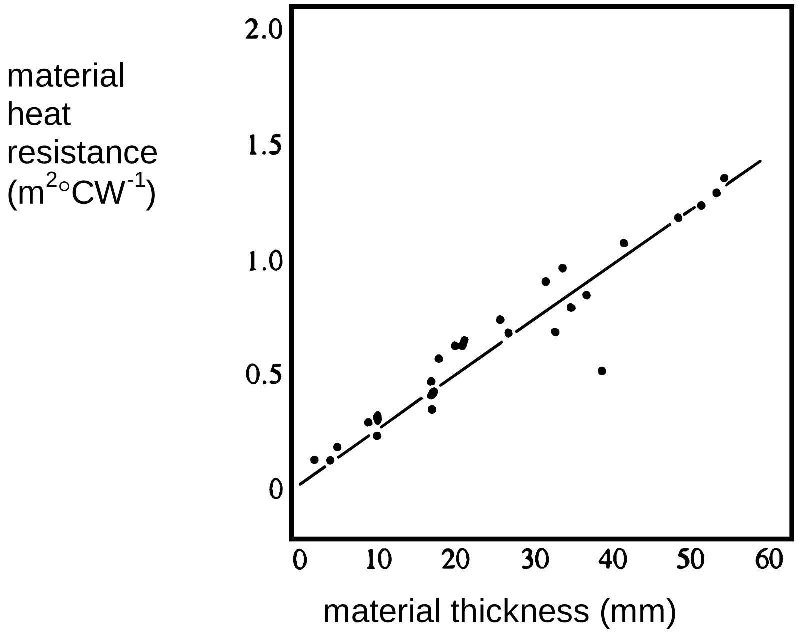

Figure 2, relation between clothing material insulation and the material thickness (Havenith and Wammes, in Lotens, 1993)

Thickness appears to be the major determinant of insulation. For normal, permeable materials, clothing material thickness also determines the major part of the clothing vapour resistance. Again, as the volume of fibres is usually low compared to the enclosed air volume, the resistance to the diffusion of water vapour through the garments is mainly determined by the thickness of the enclosed still air layer. With thin materials, the fibre component gets a more important role as there e.g. different weave characteristics affect the diffusion properties more than in thick materials (Fig. 3).

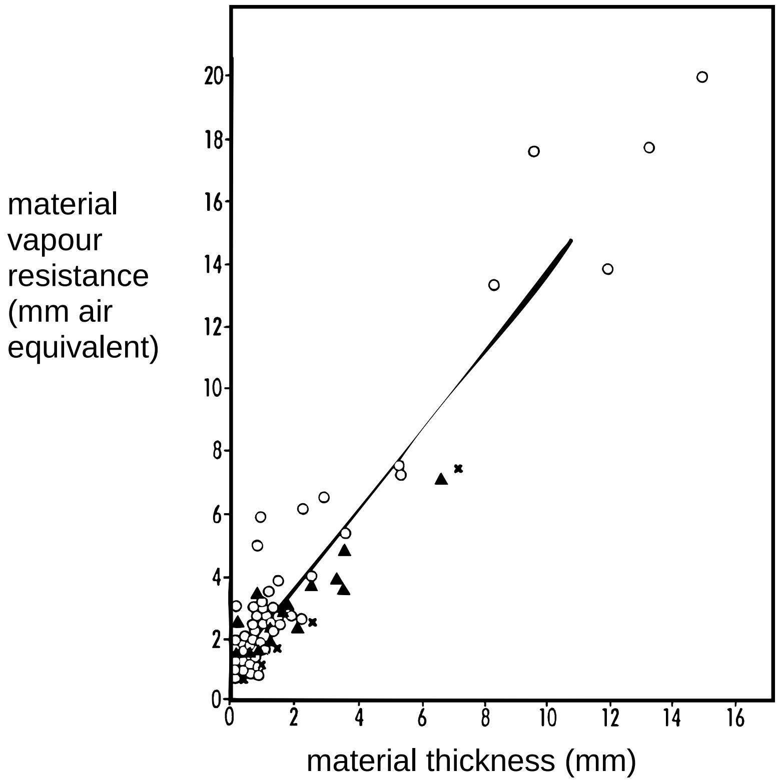

Figure 3, relation between material vapour resistance and material thickness (Lotens, 1993)

When coatings, membranes or other treatments are added to the fabrics, this will have a major effect on vapour resistance, where diffusion of vapour molecules is involved. The effect on heat resistance, where conduction is the main pathway, of such treatments is much less.

The fibres of the clothing materials do determine other properties of the clothing like air permeability and moisture absorption however, which may affect insulation and vapour resistance in special conditions like high winds and wet environments.

4.2 clothing ensembles

When not only the materials are considered but the actual insulation of a material in a garment, or when the clothing consists of more layers, the properties of the air layers between and on the outside of the material layers become important. Each material layer has a still air layer attached to its outer surface. This layer can be up to 12 mm thick, outside of which the air is insufficiently bound and will move due to temperature gradients. Thus if we express the insulation or vapour resistance of a material in units of equivalent still air thickness (the thickness of a still air layer that has the same insulation or vapour resistance as the material studied) a 2mm thick material could produce a resistance for heat or vapour transport of 12+2+12 (still air layer + material + still air layer) = 26 mm still air equivalent. If the garment or clothing ensemble would consist of several material layers the total insulation will therefore be much higher than could be expected from the insulation of the material layer alone (Fig. 4).

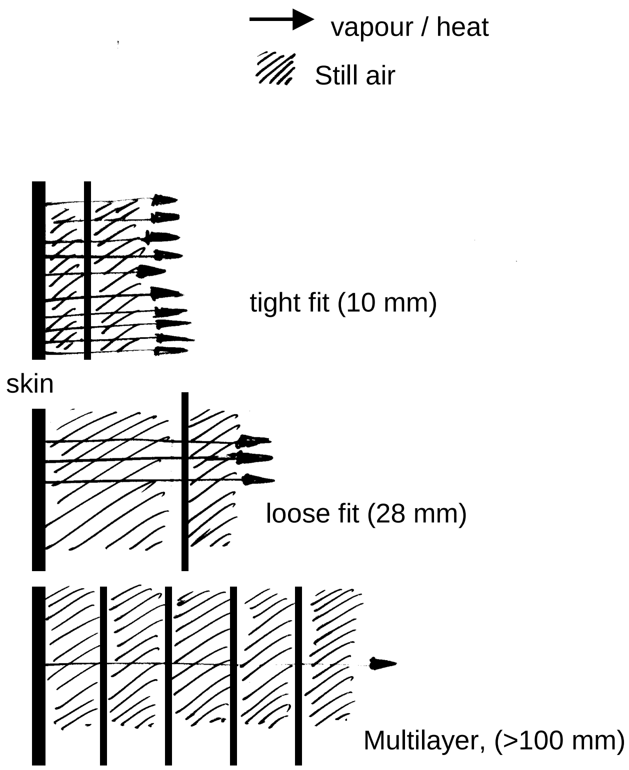

Figure 4, schematic representation of fabric and air layer contribution to total heat and vapour resistance

The total insulation of a garment will not add up to the number of layers multiplied by 26mm, however. Due to clothing design, body shape and fit the layers will not be separated enough to enclose such thick air layers. At the shoulders e.g. the layers will be directly touching, and thus there the total insulation will only be the sum of the material layers plus one air layer on the outer surface. When the clothing fits tightly, less air will be included than when it fits loosely (Fig. 4). Also, the still air layer of 12 mm mentioned above will not be reached when the garment isn't completely still, and when air movement (wind) is present.

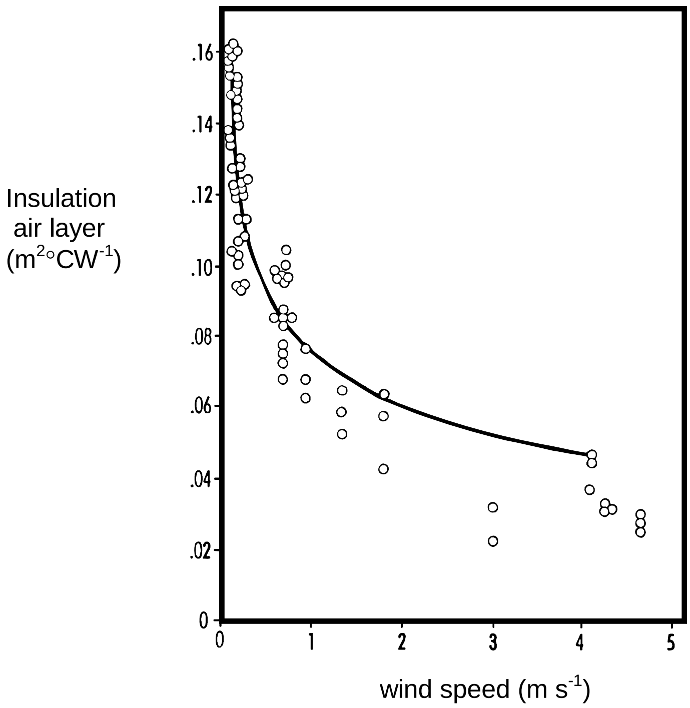

Figure 5, effect of wind speed on insulation of surface air layer (Lotens, 1993).

Air movement. When the air in the environment is moving, as usually is the case at a workplace, this air movement will disturb the still layer on the outside of the clothing. Also this air movement can disturb the air layers in the ensemble, by entering through clothing openings or, depending on the air permeability of the outer clothing layer, by penetration of the clothing fabric. The effect air movement has on the outer air layer (or on a nude persons insulative air layer), is presented in Fig. 5.

Garment movement. The garment can move by the wind, or by movements of the wearer. The wind can compress the garments, thereby decreasing its thickness, it can make the garment flutter and thereby make the enclosed air layers move. Body movement of the wearer can do the same things, and it can pump air between different clothing compartments or force it's exchange with the environment (Fig. 6).

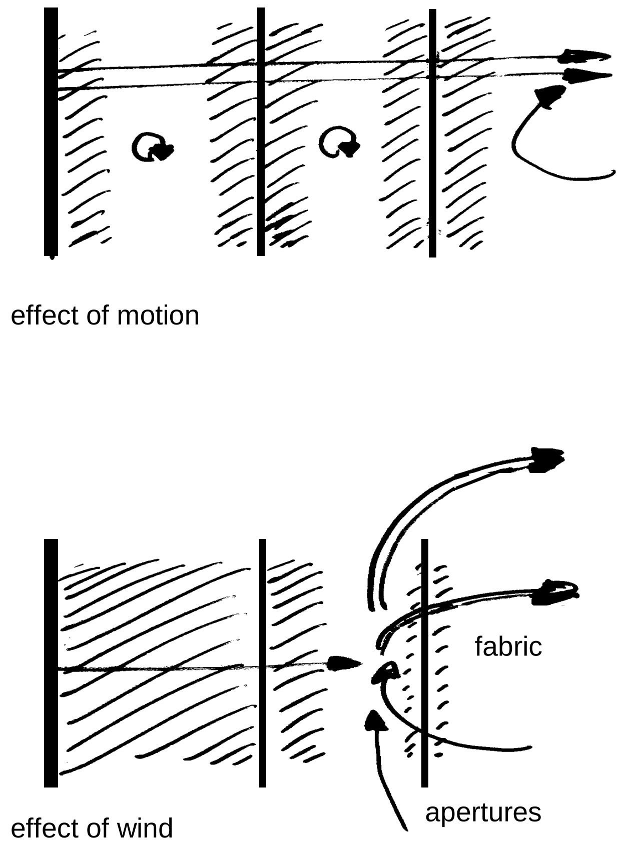

Figure 6, effect of motion and of wind on the surface and trapped air layers

4.3 Estimation of clothing heat and vapour resistance

As discussed in section 2 and 3, for the evaluation of heat stress one has to measure the climatic parameters and one needs to know the level of heat production and the clothing insulation and vapour resistance. The latter two parameters can be measured in several ways:

- using *thermal manikins*. A temperature-controlled manikin is dressed in the relevant clothing and the amount of heat needed to keep the manikin at a stable temperature is used to derive the clothing's insulation. The advantage of this method is that it gives reproducible results and is quite accurate. The disadvantage is that it is difficult to simulate human-like movements, and does not take account of differences in insulation that will occur between different wearers (shape, fit). This method will be further discussed by Holmér (1998).

- by analysing the *heat balance using human subjects* (Havenith et al, 1990, Kenney et al, 1993). Humans wearing the relevant clothing are exposed in a climatic chamber, where their physiological responses are measured and their heat balance is analysed. From the heat balance dry and evaporative heat loss can be determined and from these the heat and vapour resistance of the garment. The advantage of this method is that the clothing can be studied in reality-like circumstances as far as movements and subject population is concerned. The disadvantage is that it needs sophisticated equipment and is very time consuming.
- using *prediction models*, the clothing insulation can be calculated using a model of human geometry and data on body area covered by clothing and material thickness (McCullough et al, 1989; Lotens and Havenith, 1991). But for the actual measurements, this is the most accurate method. It is currently still too complex for widespread use, however.
- using *regression equations*. Based on clothing properties as weight, thickness, air permeability etc. the clothing insulation can be estimated (McCullough et al, 1985). This method shows a larger error than the methods above, but as properties can be measured objectively it has a low inter-observer variability.
- using *example tables*, which list data of earlier measurements on a large number of garments and ensembles. The option is either to chose from such a table an ensemble which resembles the one studied, or to add up insulations of the ensembles components, with the component's insulation again chosen from a list of earlier measured garments. The advantage is the simplicity, the disadvantage is that different observers/users tend to select different garments from the list for the same reference.

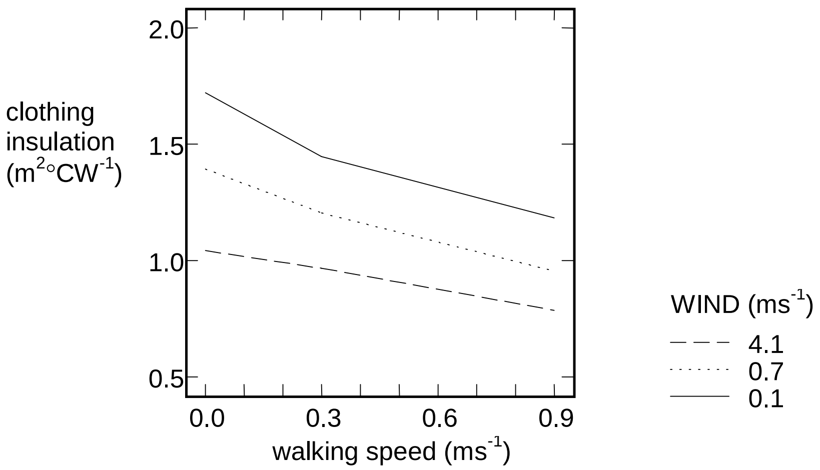

Figure 7, reduction of clothing insulation in relation to walking speed and wind speed for a 2 layer clothing ensemble (Havenith et al, 1990a).

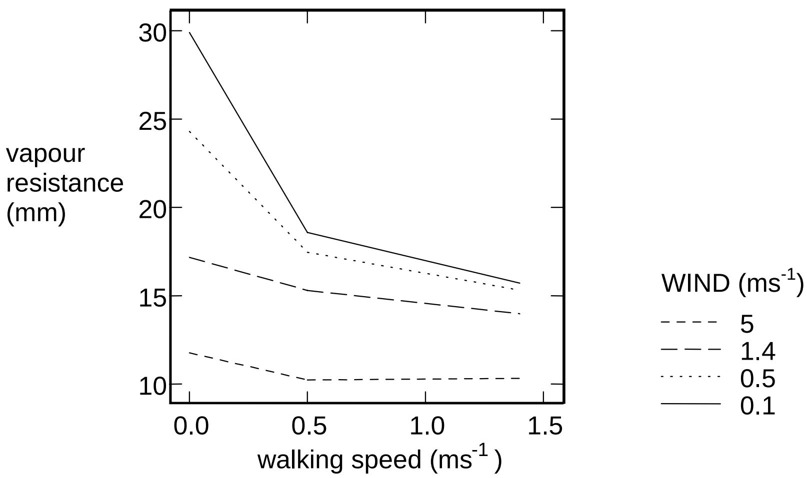

Figure 8, reduction in vapour resistance due to movement and wind for a chemical protective clothing ensemble. vapour resistance is expressed in mm of still air equivalent. (From Havenith et al, 1995)

Of the above methods, only measurements on human subjects in the actual conditions of movement and wind will provide the correct insulation results directly. Also some manikins can measure insulation while moving and can be placed in realistic wind condition. Most manikins, and all the remaining methods deliver insulation and vapour resistance values which are valid for the standing still situation in a wind-still environment only however. In these cases a correction needs to be performed, as both heat- and vapour resistance are reduced in the presence of wind and/or movement (Fig. 7 and 8). Such correction factors have been published for heat resistance (Havenith et al, 1990a; Lotens and Havenith, 1991; Nilsson, 1997) and vapour resistance (Havenith et al 1990b). Currently, data from different sources are brought together within a project of the European Community, and more general correction equations are expected to be published in the near future.

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