

Recent trends in clothing physiology

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HOLMÉR I. Recent trends in clothing physiology. *Scand J Work Environ Health* 1989;15(suppl 1):58—65. The need for high-performance protective clothing systems in space, polar, and underwater operations and in industrial environments has stimulated research in clothing physiology. New, sophisticated measurement methods, some of which are going to be international standards, have facilitated this research. Measurements with subjects have validated manikin data, but have also provided information about the dynamic character and the individual variability of thermal properties of clothing under conditions encountered in the field. Manikin measurements of the basic thermal properties of clothing (insulation and evaporative resistance) have to be corrected to apply to the user situation, due to the effects of wind, posture, body movement, and moisture absorption. Evaporative heat transfer is better defined and should be incorporated in heat exchange models and thermal indices. Important aspects of clothing physiology remain to be investigated.

Key terms: climate, evaporative resistance, insulation, methods, models, physiological reactions, thermal comfort.

Clothing is the fundamental and simple instrument by which man regulates his body heat exchange and adjusts thermally to the environment. Most people rely on their own experience when they select their clothing. This practice presents few problems when conditions are not extreme and the garments are made of conventional materials. However, as more people participate in outdoor activities, workers are exposed to more and more extreme environments, and the market is flooded with textiles, fabrics, and clothing with new, "super" properties, it is more difficult to make the right choice.

Clothing research has its own history, but it is evident that the last decade has seen a rapidly growing interest in clothing research, particularly in terms of the thermal function of clothing. This growing interest is indicated also by the number of conferences which have addressed the special problems of protective clothing (Stockholm 1981, Lyon 1983, Raleigh 1984, Tampa 1987). These environmental ergonomics conferences have included several sessions devoted to clothing research.

Although physiologists love to investigate nude subjects and, thus, circumvent many of the problems caused by clothing, an adequate assessment of the effects of climate, for practical purposes, must include the impact of clothing. This necessity was pointed out by Wissler (1), who concluded that one of three major factors limiting the currently available models for analyzing human responses to environmental stress and exercise is the "inadequate description of the clothing worn by the subject [p 272]." This presentation

is a review of some recent research in clothing physiology.

Terminology

The effect of clothing on heat exchange is determined by its thermal insulation and evaporative resistance (or permeability index). Methods are available for determining these properties. However, it is important that they be standardized on an international basis, and this work is in progress (2). The standard values for the thermal properties of clothing are the basic insulation (I_{cl}) and the basic evaporative resistance (R_{ecl}) (or permeability index, i_{cl}). Other types of insulation and resistances are presented in table 1. The total insulation (I_t) is the sum of clothing insulation and boundary air layer insulation ($I_{a/f_{cl}}$), corrected for the increased body surface area caused by clothing. Often clothing is worn under dynamic and transient conditions which differ from the "standard" conditions under which the basic values were obtained. Accordingly, in practice, the resultant insulation ($I_{cl,r}$) and the resultant evaporative resistance ($R_{ecl,r}$) differ from the basic values. In most cases the resultant values are lower than the basic values. This difference is caused by the effect of wind, body movements, and moisture condensation and absorption on microclimate ventilation. This subject will be discussed further in a later section.

Conventional physiological studies

Several physiological studies have reported the imbalance that occurs when subjects are exposed to extreme combinations of climate (often heat), work, and clothing (particularly protective clothing) (3—17). Un-

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fortunately, some of the studies do not report the thermal properties of the clothing worn and/or are designed in such a way that it is difficult to generalize the results and apply them to other than the investigated conditions. Comprehensive studies of occupational exposure to work in cold storage have been carried out (18, 19). Problems with traditional work clothing were reported, and the difficulties involved in adjusting the clothing to variation in activity and temperature in short periods of time were pointed out. Another major problem in this branch of research is extremity cooling and inappropriate protective gear for hands and feet.

Measurement of clothing heat exchange

Detailed analyses of clothing heat transfer are difficult in experiments with subjects. The investigator is left with partitional calorimetry, which allows quantitative measurements of whole-body dry and evaporative heat exchange. These kinds of measurements are, however, an important complement to the increasing number of manikin data, since they (i) validate the measurements with thermal manikins, (ii) give resultant values for comparison with basic values, and (iii)

show individual variability in heat exchange patterns with clothing.

Several investigations have reported considerable variation between manikin data and the data obtained with partitional calorimetry (6, 8, 20–28). Most of the differences can be explained by the pumping effect on the microclimate. This effect will be discussed later.

The development of new thermal manikins with multisectional, computerized heat regulation allows measurements of local heat flow and is valuable for the assessment of garment design and the composition of clothing systems (24–27, 29). Moveable manikins have contributed to the knowledge of ventilation effects and how resultant insulation differs from basic insulation under the type of movements that can be simulated by the manikin (30). The market for thermal manikins in research is increasing. The ultimate goal of a joint Scandinavian project is to construct a sweating, thermal manikin (31).

The lack of small, reliable humidity sensors have long hampered the studies of vapor transfer and evaporative heat exchange in clothing in vivo. However, several techniques are now available for the determination of vapor pressure at the skin surface and in clothing layers (21, 32). It is possible with such sen-

Table 1. Thermal properties of clothing and air — symbols, units, and definitions.

Term	Symbol	SI Unit ^a	Definitions
<i>Clothing</i>			
Basic insulation	I_{cl}	$^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Insulation of clothing alone under standard conditions (thermal manikin)
Resultant insulation	$I_{cl,r}$	$^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Insulation under actual conditions
Basic evaporative resistance	R_{ecl}	$\text{kPa} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Evaporative resistance under standard conditions
Resultant evaporative resistance	$R_{ecl,r}$	$\text{kPa} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Evaporative resistance under actual conditions
Permeability index	i_{cl}	No dimension	Permeability of clothing layers (fabric layers) under standard conditions
Permeability index	$i_{cl,r}$	No dimension	Resultant value under actual conditions
<i>Air</i>			
Air insulation	I_a	$^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Insulation of boundary air layer under standard conditions (thermal manikin)
Resultant air insulation	$I_{a,r}$	$^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Insulation of the boundary air layer under actual conditions
Basic evaporative resistance	R_{ea}	$\text{kPa} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Evaporative resistance under standard conditions
Resultant evaporative resistance	$R_{ea,r}$	$\text{kPa} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Evaporative resistance under actual conditions
Permeability index	i_a	No dimension	Basic value under standard conditions
Permeability index	$i_{a,r}$	No dimension	Resultant value
<i>Clothing and air layer</i>			
Total insulation	I_T	$^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Basic insulation plus basic boundary layer insulation under standard conditions, $I_{cl} + I_a/f_{cl}$
Resultant total insulation	$I_{T,r}$	$^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Total insulation under actual conditions, $I_{cl,r} + I_{a,r}/f_{cl}$
Total evaporative resistance	R_{eT}	$\text{kPa} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Total evaporative resistance of clothing and boundary air layer under standard conditions
Resultant evaporative resistance	$R_{eT,r}$	$\text{kPa} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Total evaporative resistance under actual conditions
Permeability index	i_m	No dimension	Permeability of clothing and boundary air layers under standard conditions (thermal manikin) (Woodcock i_m)
Permeability index	$i_{m,r}$	No dimension	Resultant value

^a Insulation is often expressed in clo units, 1 clo = $0.155^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$.

sors to measure directly the skin wettedness factor, particularly local values. This possibility opens up a new field of research on factors determining evaporative heat exchange and thermal comfort.

Thermal insulation

The basic insulation of a garment or clothing system (I_{cl}) is measured under standardized conditions with a thermal manikin (2). The manikin is static, standing in a climatic chamber at a very low air velocity (v_a) ($<0.15 \text{ m} \cdot \text{s}^{-1}$). Due to wind, moisture absorption, and the movement and posture of the wearer, the resultant insulation ($I_{cl,r}$) provided by the garment, when used, is often less than I_{cl} . This subject has been extensively studied by Olesen and his co-workers (25, 26, 30). They carried out a series of experiments on different types of garments with a moveable manikin and with subjects. They found that (i) I_{cl} is reduced by the effect of wind and body movements, (ii) I_{cl} was reduced by 5–26 % depending on the air permeability of the outer fabric layer, (iii) I_{cl} was reduced by 14–18 % during bicycling and by 5–46 % during walking compared to standing, garment design being an important determinant, and (iv) insulation values measured with subjects were comparable to manikin values for the same clothing ensembles and activities.

Similar studies have been carried out by Umbach (27, 33) and Mecheels & Umbach (24). These researchers have developed a standardized technique for evaluating clothing systems which includes an investigation of the pumping effect.

It is important to realize that the basic insulation value, considered as a characteristic of a garment, does not provide a straight answer as to the protective value of a garment against dry heat loss. This factor is of particular importance in cold environments. The I_{cl} value provided with a clothing ensemble has to be corrected according to the conditions of use to give a more realistic value of its resultant insulation. Unfortunately, the information on this subject is limited, and more work is required. Whenever required insulation or evaporative resistance is computed with a mathematical model, the values are resultant. Selection of appropriate clothing, on the other hand, is made with the basic values, which, therefore, must be corrected to a resultant value.

Evaporative heat exchange

The inability of most heat exchange models to predict, accurately, the effects of wearing protective clothing is a good indicator of the lack of important knowledge about evaporative heat transfer mechanisms. However, this subject has interested many scientists in recent years, and new methods have facilitated the investigations. There are at least three different approaches to the determination of the resistance to

evaporative heat exchange by clothing. It can be based on permeability indices, a permeation efficiency factor, or a direct measurement of evaporative resistance. Evaporative heat exchange is calculated by

$$\begin{aligned} E &= (p_{sk} - p_a) / R_{e,T} \\ &= (p_{sk} - p_a) 16.7 f_{cl} \cdot h_c \cdot F_{pcl} \quad (\text{equation 1}) \\ &= (p_{sk} - p_a) 16.7 i_m / I_{T,r} \end{aligned}$$

where $p_{sk} - p_a$ is the vapor pressure between the skin and the environment in kilopascals. The other factors are discussed in the next two sections. (See also table 1.)

Permeation indices

The first introduction of a permeability index was made by Woodcock (34). His permeability index (i_m) has been extensively used by Goldman and his co-workers (20, 25, 36) and Umbach (27, 33). A more general approach to the analysis of vapor transfer in clothing systems has been applied by Lotens & Van de Linde (37) and Oohori et al (38), who introduced a permeability ratio for clothing layers (i_{cl}) and for the boundary air layer (i_a). The rationale behind and the relationship between the different permeability indices and the permeation efficiency factors has recently been demonstrated (38). All permeability indices are defined by the ratio between the Lewis number for the layer and the Lewis number for an air layer of equivalent thickness. The latter number is a constant and averages 16.7 in this temperature range. The index values vary between 0 and 1 and are dimensionless. The indices are defined and presented in table 2.

Evaporative resistance

Evaporative resistance may be directly measured with subjects by partitional calorimetry and measurements of the vapor pressure gradient between the skin and the environment (21, 32). An example is illustrated in figure 1. With the use of the continuous body weight change and vapor pressure measurements, the total evaporative resistance ($R_{e,T}$) can be determined. The technique is not suitable as a standard, but it gives valuable information about the variation between individuals and garments. It is also suitable for the analysis of the resultant values. Examples of values obtained with this technique are given in table 3 (39).

The standard approach to calculating evaporative heat exchange is to use the i_m index (21, 33, 36) or the permeation efficiency factor (F_{pcl}) (40–42):

$$\begin{aligned} R_{e,T} &= 1 / (16.7 f_{cl} \cdot h_c \cdot F_{pcl}) \\ &= 0.06 I_{T,r} / i_m \quad (\text{equation 2}) \end{aligned}$$

The F_{pcl} factor is dimensionless, varies between 0 and 1, and defines the reduced efficiency of evaporative heat exchange caused by clothing (41). The basic formula presents F_{pcl} as a function of basic clothing insulation (I_{cl}) and the convection coefficient (h_c). This relation is valid for light, porous clothing, and

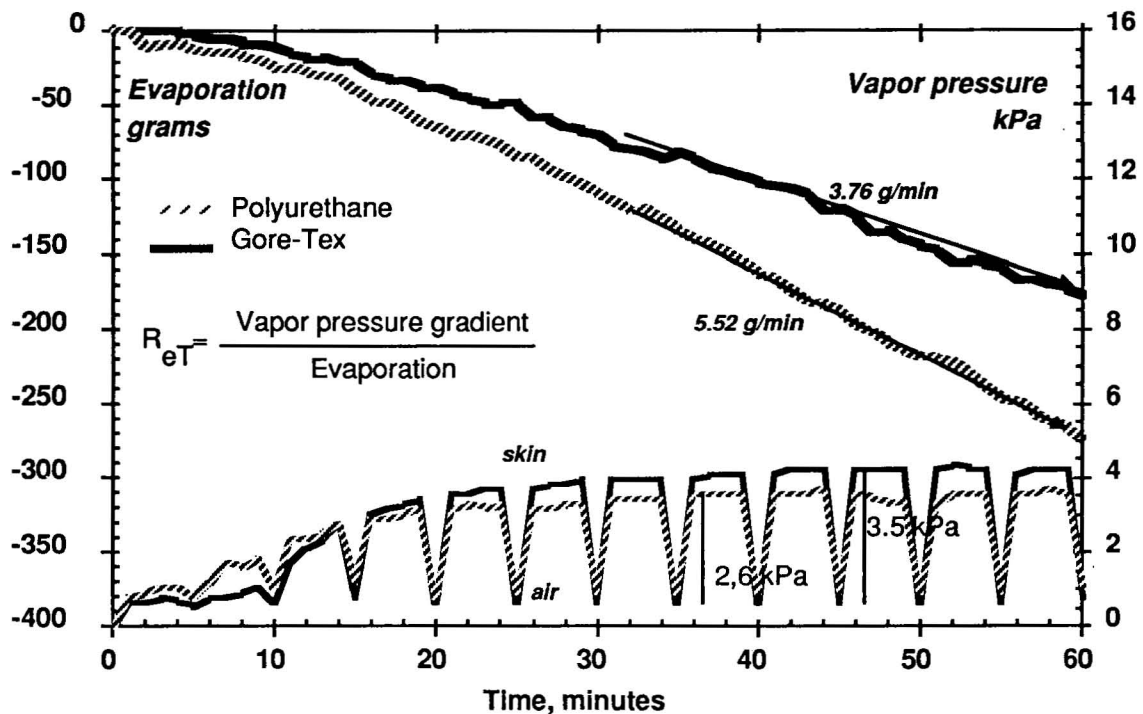


Figure 1. Determination of the evaporative resistance of clothing from continuous measurements of evaporative heat loss (sweat loss) and skin to the ambient water vapor pressure gradient. The results are from one subject bicycling for 60 min in impermeable and semipermeable rainwear (32).

Table 2. Permeation ratios for water vapor transfer through layers of clothing and air. For an explanation of the symbols see table 1. R_{ecl} is the evaporative resistance of clothing (or fabric) layers, excluding the boundary air layer.

Layer	Index	Definition	Lewis number	Measurement
Air	i_a	h_e/h_c	16.7	—
Clothing/fabric	i_{cl}	$0.06 I_{cl}/R_{ecl}$	I_{cl}/R_{ecl}	"Wet" plate or "wet" manikin
Clothing and air	i_m	$0.06 I_T/R_{eT}$	I_T/R_{eT}	"Wet" manikin

Table 3. Thermal properties of clothing ensembles from various sources (9, 29, 32, 39). The R_{eT} values were calculated on the basis of equation 15 from table values. The i_{cl} values were reported by Oohori et al (38). For an explanation of the symbols see table 1. (KSU = Kansas State University)

Clothing	i_{cl} (clo)	i_T (clo)	i_m^a	i_{cl}^a	R_{eT} ($\text{Pa} \cdot \text{m}^2 \cdot \text{W}^{-1}$)
Basic, manikin data					
None (ie, manikin nude)	0	0.8	0.47	0	17
Cotton shirt and trousers (KSU uniform), underwear, socks, shoes	0.65	1.25	0.39	0.32	30
Coverall, T-shirt, underwear, socks, shoes	0.84	1.41	0.39		34
Cotton shirt and pants, underwear, T-shirt, belt, socks, shoes	1.00	1.51	0.32	0.27	44
Resultant, subject data					
Coveralls, long underwear, socks, shoes	0.84	1.5 (1.2 ^b)	0.59 ^b		19 ^b
Rainwear (Goretex ⁺), coveralls, long underwear, socks, shoes	1.29	1.9 (1.3 ^b)	0.36 ^b		34 ^b
Rainwear (nylon coated with polyurethane), coveralls, long underwear, socks, shoes	1.29	1.9 (1.3 ^b)	0.16 ^b		77 ^b
Chemical protective suit (impermeable), coveralls, long underwear, socks, shoes	1.4	1.9 (1.1 ^b)	0.06 ^b		180 ^b

^a No dimension.

^b Obtained with measurements on subjects during work in a climatic chamber (9, 32).

the permeability properties of the garments are not considered (41):

$$F_{pcl} = 1/(1 + 2.22 \cdot f_{cl} \cdot h_c \cdot I_{cl}). \quad (\text{equation 3})$$

A more general definition of the F_{pcl} factor, including the i_{cl} factor, is (38):

$$F_{pcl} = 1/(1 + f_{cl} \cdot h_c \cdot I_{cl}/i_{cl}). \quad (\text{equation 4})$$

R_{ct} may now be expressed in terms of I_{cl} , h_c , and i_{cl} . Calculating F_{pcl} is not required:

$$R_{ct} = R_{cu} + R_{ccl} = [0.06/(f_{cl} \cdot h_c)] + (0.06/i_{cl}) \cdot I_{cl}. \quad (\text{equation 5})$$

It follows from equations 3 and 4 that i_{cl} in equation 3 is a constant, ie, $1/2.22 = 0.45$, which is a typical value for normal, porous, indoor clothing (38).

It follows from equation 5 that R_{ct} increases rapidly with low index values and with increased insulation. Accordingly, evaporative heat loss decreases at a given vapor pressure gradient (equation 1). A constant value for i_{cl} can therefore not be used whenever clothing with lowered moisture permeability is used. It is recommended that predictive models and indices, based on the original F_{pcl} formula, be modified to include i_{cl} . More work, however, is required to validate this approach, particularly for protective clothing. Values of R_{ct} , i_{cl} , and i_m are given for different types of clothing in table 3.

The permeability index of a clothing system, i_m , is measured with a "wetted" thermal manikin (20, 35, 36), and the permeability index for clothing fabric layers, i_{cl} , is measured with a "skin model" or a "wetted" manikin (27, 37, 38).

Microclimate ventilation

As already mentioned, the variability in the thermal properties of clothing is related to the ventilation of the air in and between clothing layers. The combination of garment design and body movements causes air to be pumped in and out through garment openings and through the fabric. The more impermeable clothing is, the more important this pumping effect is in enabling some kind of "evaporative heat loss." The trace gas technique, first developed by Birnbaum & Crockford (43), has been useful in the evaluation of microclimate ventilation. It is a fast, and simple, method that can be used for analyzing the effect of garment design and different types of work movements (44, 45). Figure 2 shows a theoretical calculation of required ventilation for a garment ensemble of different permeability (46). The required evaporation rate was 120 W ($180 \text{ g} \cdot \text{h}^{-1}$). It is evident that (i) with lowered permeability, the ventilation requirement increases rapidly, and (ii) in the cold much more ventilation is required at the same permeability to prevent condensation.

Clothing in mathematical models and thermal indices

It was stated already in the introduction that the lack of an adequate description of clothing was a limitation to predictions of thermal effects with mathematical models (1). Indeed, most climate indices do not consider the thermal properties of clothing and, therefore, only apply to normal everyday clothing. The wet bulb globe temperature (WBGT) index (47) is such an index; it requires special correction to be used with special clothing (48).

Most rational climate indices, including the proposed new standard of the International Organization for Standardization (SW_{req}) (2), use the original F_{pcl} format for calculating evaporative heat exchange. As previously pointed out, this is a special case, applicable only to light, porous everyday clothing, and should be replaced by the general format based on the moisture permeability of clothing (i_{cl}).

The same situation is valid for the effective temperature (ET^*) index (42). A recent modification of ET^* takes into consideration the general equation (40). This version is the most sophisticated climate index so far, in terms of incorporating the moisture permeation properties of clothing. However, the experimental validation of this method for less impermeable garments has yet to be done.

In the comfort zone the predicted mean vote (PMV) index (55) takes thermal insulation but not moisture permeability into account. This is a small problem, since the field of application of the method is mostly at low activities requiring none or little sweating. If, however, it is applied to higher activities with special clothing, the error might be significant, as the evaporative heat exchange is overestimated. A correction of the method can be made to account also for such conditions (40, 50).

Few climate indices are available for cold environments. Required insulation (IREQ) has been proposed as a method for assessing cold stress (51). In this model clothing heat exchange is based on both clothing insulation and evaporative resistance.

If values for both insulation and evaporative resistance (permeability) are incorporated in the existing models and indices, their field of application becomes wider and the predictive power increases. It should be emphasized, however, that, despite the introduction of the i_{cl} index, several problems remain as to a correct description of the impact of clothing on evaporative (and conductive) heat exchange. The thermal properties of clothing previously described (I_{cl} and i_{cl}) relate to a standard condition, but clothing is worn under different conditions. The problems are related to the effects of wind, wear movement, and moisture absorption, all of which affect the microclimate and thermal properties. In other words, the resultant insulation and evaporative resistance under the actual wearing conditions are likely to be different from (in most

cases lower than) the basic values. With a few exceptions little attention has been paid to these problems.

There are two ways to proceed. One is to stay with the present set of equations to describe heat exchange and realize that resultant values for clothing are required. Since thermal properties are unique for each garment, this method requires correction factors to translate basic values to resultant values. This school is well represented by Goldman and his co-workers (20, 35, 36) and the Hohenstein group (24, 27, 33). Goldman determines "pumping coefficients" for each garment ensemble to derive its "effective" (= resultant) value. Mecheels & Umbach (24) have developed a technique by which each garment is measured during dynamic conditions, ie, with a "walking" manikin. The values obtained during this measurement are used in their prediction model and serve as a kind of correction. Indeed, with this approach, more effort should be spent analyzing how basic values change under different wearing conditions.

The other approach requires the development of equations which describe, in a general format, the impact of, eg, wind, posture, body movement, etc. The concept of a relative air velocity (v_{ar}) is in line with this approach. However, the equation used by most models [$v_{ar} = v_a + 0.0052 (M-58)$] (2) needs better validation for different types of activity. More work is required on this subject.

Clothing and comfort criteria

Of great importance for the assessment of the thermal impact of a clothing system are the physiological criteria. What is thermal comfort? What is physiologically acceptable? What are the tolerance limits? The physiological factors operating in all heat exchange models are mean skin temperature and sweat loss. With respect to mean skin temperature, the comfort criteria (52) appear to apply also to cold conditions (8). The sweat loss may be expressed in terms of a required evaporative heat loss (52) or as a required skin wettedness (40, 41). The concept of a required evaporative heat loss does not apply to cold conditions (8) or when special clothing is worn (eg, protective clothing) (37, 40, 50). The moisture permeability of clothing is not considered with this approach. Skin wettedness is related to the sensation of comfort or, preferably, warm discomfort (40). With the skin wettedness approach the moisture permeation properties of clothing can be included.

Nonthermal factors

Several investigators have shown that the perception of comfort and the acceptance of a garment does not only depend on thermal factors (53—55). Garment fit, moisture buffering properties, and mechanical proper-

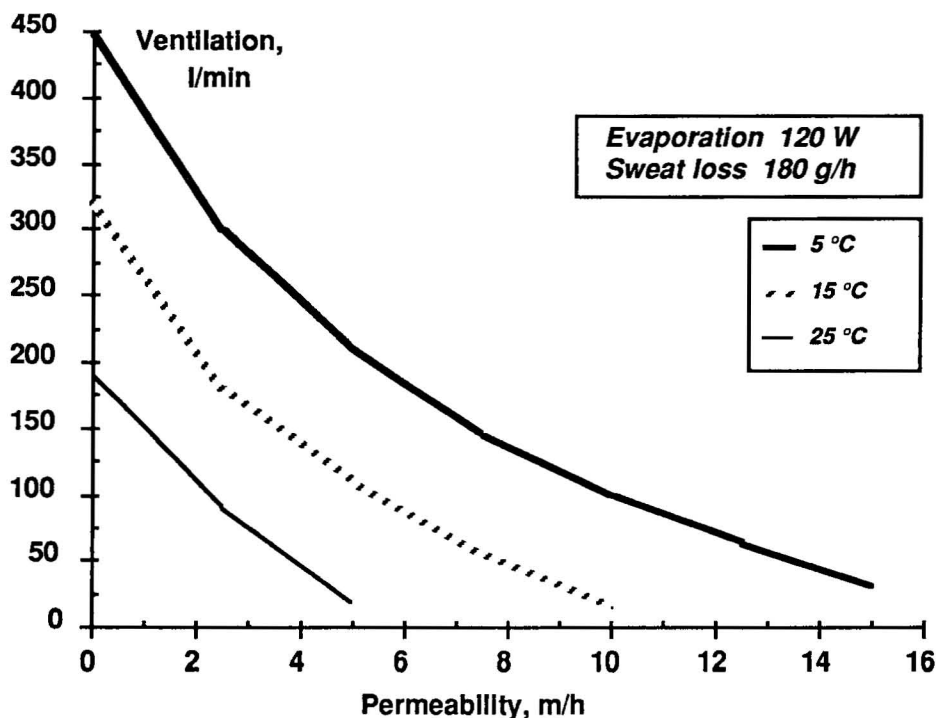


Figure 2. Required ventilation rates at three ambient temperatures as a function of permeability to prevent condensation. The values were calculated for a garment ensemble, and the required evaporation was 120 W (180 g · h⁻¹) [modified from Lotens (46)].

ties of fibers and fabrics are correlated with the sensation of comfort. Umbach (27, 33) has extensively studied the moisture buffering capacities of underwear of different material and developed test methods that measure relevant properties. Gwosdow et al (53) found that the friction between the fabric and the skin increased sharply when wettedness was 0.25–0.30. More work is required to investigate the interrelationship between thermal and nonthermal factors and their importance for thermal sensation.

Future research

Several aspects of the thermal function of clothing have been reviewed, and some areas have been identified as poorly integrated or understood due to lack of knowledge. Some of the most significant problems to be investigated in both chamber and field experiments may be summarized and conclude this review of recent trends in clothing physiology: (i) the variability in the thermal properties of clothing under wearing conditions (wind, posture, effects of body movements, etc.), (ii) the effects of moisture absorption and the condensation and reevaporation of sweat in clothing, (iii) the effect of clothing on heat exchange during transient conditions (changing climate, intermittent activity, etc), (iv) the effects of nonuniform clothing distribution, (v) the validation of predictive models for special clothing (eg, protective clothing), (vi) the validation of predictive models with basic and resultant values, respectively, for the thermal properties of clothing, (vii) the validation of different physiological criteria for the assessment of comfort, acceptance and tolerance to all thermal environments, and (viii) non-thermal factors and their effects on clothing function and comfort.

Acknowledgments

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References

- Wissler EH. A review of human thermal models. In: Mekjavic IB, Banister EW, Morrison JB, ed. *Environmental ergonomics*. London: Taylor & Francis, 1988: 267–85.
- International Organization for Standardization. *Hot environments — analytical determination and interpretation of thermal stress using calculation of required sweat rates*. Geneva: International Organization for Standardization, 1987. (ISO/DIS 7933.)
- Beckett WS, Davis JE, Vroman N, Nadig R, Fortney S. Heat stress associated with the use of vapor-barrier garments. *J Occup Med* 1986;28:411–4.
- Carter BJ, Cammermeyer M. 1985. Biopsychological responses of medical unit personnel wearing chemical defense ensemble in a simulated chemical warfare environment. *Milit Med* 1985;150:239–49.
- Eissing G. Protective clothing: study in induced thermal strain and in protection against thermal radiation. *ASHRAE Trans* 1984;90(pt 1b):1099–115.
- Haymes EM, Dickinson AL, Malville N, Ross RW. Effect of wind on the thermal and metabolic responses to exercise in the cold. *Med Sci Sports Exerc* 1982;14: 41–5.
- Hettinger T, Eissing G, Bolle D, Urlaub G. *Persönliche Schutzausrüstungen*. Dortmund: Belastung und Beanspruchung, Bundesanstalt für Arbeitsschutz und Unfallforschung, 1980. (Forschungsbericht Nr 227).
- Holmér I. Heat exchange by sweating in cold protective clothing. In: *Centre de Recherche du Service de Santé des Armées. Aspect médicaux et biophysique des vêtements*. Lyon: Centre de Recherche du Service de Santé des Armées, 1984:306–11.
- Holmér I. Termofysiologiska egenskaper hos arbets- och skyddskläder [Thermophysiological properties of work and protective clothing]. Stockholm: Arbetarskyddsverket, 1986. (Arbete och hälsa 12:1–62.)
- Light IM, Gibson MG, Avery AI. Sweat evaporation and thermal comfort in helicopter passenger immersion suits. *Ergonomics* 1987;30:793–803.
- Sköldström B. Physiological responses of fire fighters to workload and thermal stress. *Ergonomics* 1987;30: 1589–97.
- Sköldström B, Holmér I. A protective garment for hot environments with improved evaporative heat transfer. In: *Centre de Recherche du Service de Santé des Armées. Aspects médicaux et biophysiques des vêtements de protection*. Lyon: Centre de Recherche du Service de Santé des Armées, 1983:289–94.
- Smolander J, Louhevaara V, Ahonen M. Clothing, hypothermia and long-distance skiing. *Lancet* 1986;2: 226–7.
- Smolander J, Louhevaara V, Korhonen O. Physiological strain in work with gas protective clothing at low ambient temperatures. *Am Ind Hyg Assoc J* 1985;46: 720–3.
- Tanaka M. Metabolic and thermal responses of man wearing protective clothing to various degree of cold stress. *Eur J Appl Physiol* 1978;39:137–44.
- White MK, Hodous TK. Reduced work tolerance associated with wearing protective clothing and respirators. *Am Ind Hyg Assoc J* 1987;48:304–10.
- Woon SJ, Tokura H. Effects of wearing two different forms of garment on thermoregulation in men resting at 10°C. *Eur J Appl Physiol* 1988;57:627–31.
- Aptel M. Le travail au froid artificiel dans l'industrie alimentaire. *Cah Notes Doc Secur Hyg Trav* 1987;126: 47–55.
- Nielsen R. Clothing and thermal environments. *Appl Ergon* 1986;17:47–57.
- Givoni B, Goldman RF. Predictive rectal temperature response to work, environment and clothing. *J Appl Physiol* 1972;32:812–22.
- Gonzalez RR, Cena K. Evaluation of vapor permeation through garments during exercise. *J Appl Physiol* 1985;58:928–35.
- Holmér I. Heat exchange and thermal insulation compared in woolen and nylon garments during wear trials. *Text Res J* 1985;55:511–8.
- Kenney WL, Lewis DA, Hyde DE, et al. Physiologically derived critical evaporative coefficients for protective clothing ensembles. *J Appl Physiol* 1987;63:1095–9.
- Mecheels J, Umbach KH. *Thermophysologische Eigenschaften von Kleidungssystemen*. Meiland Textilber 1976;57:1029–32 & 1977;58:73–81.
- Nielsen R, Olesen BW, Fanger PO. Effect of physical activity and air velocity on the thermal insulation of clothing. *Ergonomics* 1985;28:1617–31.
- Olesen BW, Nielsen R. Thermal insulation of clothing measured on a movable thermal manikin and on human

- subjects. Copenhagen: Technical University of Denmark, 1983. (ECSC programme research no 7206/00/914.)
27. Umbach KH. Methods of measurement for testing physiological requirements of civilian, work and protective clothing and uniforms. *Melliand Textilber* 1987;68: 857—65.
 28. Vogt JJ, Meyer JP, Candas V, Libert JP, Sagot JC. Pumping effects on thermal insulation of clothing worn by human subjects. *Ergonomics* 1983;26:963—74.
 29. McCullough EA, Arpin EJ, Jones B, Konz SA, Rohles FH. Heat transfer characteristics of clothing worn in hot industrial environments. *ASHRAE Trans* 1982;1:1077—94.
 30. Olesen BW, Sliwinski E, Madsen TL, Fanger P. Effect of body posture and activity on the thermal insulation of clothing: measurements by a moveable thermal manikin. *ASHRAE Trans* 1982;88(pt 2):791—805.
 31. Meinander H. Towards a sweating thermal manikin for evaluation of clothing systems and thermal environments [Abstract]. In: Ilmarinen R, Päsche A, ed. Proceedings of 3rd international conference on environmental ergonomics, 8—12 August 1988, Helsinki, Finland. Helsinki: Organizing Committee of 3rd International Conference on Environmental Ergonomics, 1988:66.
 32. Holmér I, Elnäs S. Physiological evaluation of the resistance to evaporative heat transfer by clothing. *Ergonomics* 1981;24:63—74.
 33. Umbach KH. Physiological tests and evaluation models for the optimization of the performance of protective clothing. In: Mekjavic IB, Banister EW, Morrison JB, ed. *Environmental ergonomics*. London: Taylor & Francis, 1988:139—161.
 34. Woodcock AH. Moisture transfer in textile systems, part 1. *Text Res J* 1962;32:628—33.
 35. Goldman RF. Standards for human exposure to heat. In: Mekjavic IB, Banister EW, Morrison JB, ed. *Environmental ergonomics*. London: Taylor & Francis, 1988:99—129.
 36. de van Martin H, Goldman R. Comparison of physical and physiological methods of evaluating the thermal strain associated with wearing protective clothing. *Ergonomics* 1972;15:337—42.
 37. Lotens WA, Van de Linde EJG. Insufficiency of current clothing description. In: Centre de Recherche du Service des Santé des Armées. Aspects médicaux et biophysiques des vêtements de protection. Lyon: Centre de Recherche du Service des Santé des Armées, 1984: 250—9.
 38. Oohori T, Berglund LG, Gagge AP. Comparison of current two-parameter indices of vapor permeation of clothing — as factors governing thermal equilibrium and human comfort. *ASHRAE Trans* 1985;90(pt 2):85—101.
 39. International Organization for Standardization. Estimation of the thermal characteristics of a clothing ensemble. Geneva: International Organization for Standardization. (ISO/DP 9920.)
 40. Gagge AP, Fobelets AP, Berglund LG. A standard predictive index of human response to the thermal environment. *ASHRAE Trans* 1986;92(pt 2):709—31.
 41. Nishi Y, Gagge AP. Moisture permeation of clothing: a factor governing thermal equilibrium and comfort. *ASHRAE Trans* 1970;76(pt 1):137—45.
 42. Nishi Y, Gagge AP. Effective temperature scale useful for hypo- and hyperbaric environments. *Aviat Space Environ Med* 1977;48:97—107.
 43. Birnbaum RR, Crockford GW. Measurement of the clothing ventilation index. *Appl Ergon* 1978;9:194—200.
 44. Lotens WA, Havenith G. Ventilation of rainwear determined by a trace gas method. In: Mekjavic IB, Banister EW, Morrison JB, ed. *Environmental ergonomics*. London: Taylor & Francis, 1988:162—76.
 45. Sullivan PJ, Mekjavic IB, Kakitsuba N. Ventilation index of helicopter pilot suits. *Ergonomics* 1987;30: 1053—61.
 46. Lotens WA. Clothing design for work in cold. *Artic Med Res* 1987;46:3—12.
 47. International Organization for Standardization. Hot environments — estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature). Geneva: International Organization for Standardization, 1982. (ISO 7243.)
 48. Kenney WL. WBGT adjustments for protective clothing. *Am Ind Hyg Assoc J* 1987;48:A-576—7.
 49. International Organization for Standardization. Moderate thermal environments — determination of the PMV and PPD indices and specification of the conditions for thermal comfort. Geneva: International Organization for Standardization, 1984.
 50. Holmér I. Moisture permeation of clothing and thermal comfort. In: Berglund B, Lindvall T, Sundell J, ed. *Indoor air. Vol 5*. Stockholm: Council for Building Research, 1984:321—7.
 51. Holmér I. Required clothing insulation (IREQ) as an analytical index of cold stress. *ASHRAE Trans* 1984;90(pt 1):1116—28.
 52. Fanger PO. *Thermal comfort*. Copenhagen: Danish Technical Press, 1970.
 53. Gwosdow AR, Stevens JC, Berglund LG, Stolwijk JAJ. Skin friction and fabric sensations in neutral and warm environments. *Text Res J* 1986;56:574—80.
 54. Hollies NRS, Custer AG, Morin CJ, Howard ME. A human perception analysis approach to clothing comfort. *Text Res J* 1979;49:557—64.
 55. Li Y, Keighley J. Relations between fibre, yarn and fabric mechanical properties and subjective sensory responses in wear trials [Abstract]. In: Ilmarinen R, Päsche A, ed. Proceedings of 3rd international conference on environmental ergonomics, 8—12 August 1988, Helsinki, Finland. Helsinki: Organizing Committee of 3rd International Conference on Environmental Ergonomics, 1988:38.