

Dry and Wet Heat Transfer Through Clothing Dependent on the Clothing Properties Under Cold Conditions

**Mark G.M. Richards
René Rossi**

EMPA, Swiss Federal Laboratories for Materials Testing and Research, St. Gallen, Switzerland

Harriet Meinander

Tampere University of Technology, Tampere, Finland

Peter Broede

Institut für Arbeitsphysiologie an der Universität Dortmund, Dortmund, Germany

Victor Candas

Centre National de la Recherche Scientifique, Strasbourg, France

Emiel den Hartog

TNO, The Netherlands

Ingvar Holmér

Lund University, Lund, Sweden

Wolfgang Nocker

W.L. Gore, Germany

George Havenith

Department of Human Sciences, Loughborough University, Loughborough, UK

The purpose of this study was to investigate the effect of moisture on the heat transfer through clothing in relation to the water vapour resistance, type of underwear, location of the moisture and climate. This forms part of the work performed for work package 2 of the European Union THERMPROTECT project. Thermal manikin results of dry and wet heat loss are presented from different laboratories for a range of 2-layer clothing with similar dry insulations but different water vapour permeabilities and absorptive properties. The results obtained from the different manikins are generally consistent with one another. For each climate, total wet heat loss is predominately dependent on the permeability of the outer layer. At 10 °C, the apparent evaporative heat loss is markedly higher than expected from evaporation alone (measured at 34 °C), which is attributed to condensation within the clothing and to increased conductivity of the wet clothing layers.

heat transfer moisture condensation wet conduction clothing systems

This work was funded as European Union GROWTH programme project "THERMPROTECT, Assessment of Thermal Properties of Protective Clothing and Their Use", contract G6RD-CT-2002-00846.

Correspondence and requests for offprints should be sent to Mark G.M. Richards, EMPA, Laboratory for Protection and Physiology, Lerchenfeldstrasse 5, CH-9014 St. Gallen, Switzerland. E-mail: <mark.richards@empa.ch>.

1. INTRODUCTION

The presence of moisture within clothing can increase the wearer's heat loss dramatically [1, 2, 3], with the evaporation of sweat from the surface of the skin usually being one of the most important methods of losing excess body heat. However, personal protective clothing (PPC) tends to hinder the heat and moisture transfer from the wearer, which can lead to heat stress, even under cold conditions, if a strenuous workload is undertaken [4]. Although standards for predicting heat and cold stress [5] continue to be developed (e.g., Malchaire, Piette, Kampmann, et al. [6]), current methods of describing the heat transfer through PPC are still inadequate and inaccurate [7].

Heat and moisture transport through clothing involve complex processes and are coupled through evaporation, condensation, sorption and desorption of moisture [8, 9, 10]. However, at present, standards for predicting heat and cold stress [5] are based on a body heat balance equation (as defined in Blatteis, Boulant, Cabanac, et al. [11]), which does not take such coupling into account. The total heat exchange between the skin and the environment over the clothing is defined in such standards as being purely the sum of its dry and evaporative heat exchanges. These heat exchanges are estimated using the dry thermal resistance and water vapour resistance (or permeability) values of the clothing worn, which have been measured without the presence of additional moisture. Nevertheless additional moisture is often present in clothing, particularly from sweat which accumulates during and following exercise. Such moisture reduces the effective thermal insulation of the clothing, can increase the effective water vapour resistance and, under cold conditions, increases the total heat loss from the wearer [1, 2, 3, 22].

The European Union research project THERMPROTECT, entitled "Thermal Properties of Clothing and Their Use", was set up to provide data on and models to be used to improve standards for the use of PPC. Work package (WP) 2 of this project investigated the effects of moisture on the heat transfer through clothing in relation to the water vapour resistance, type of

underwear, location of the moisture and climate. An extensive series of material tests, manikin experiments and human trials was carried out by seven European research institutes [12].

As part of THERMPROTECT WP2, the aim of this study was to use manikin results to investigate the effect of moisture on the heat transfer through two-layer clothing combinations with different properties in order to gain a better understanding of the heat transfer processes involved when working in the cold.

2. METHODS

2.1. Materials/Clothing Investigated

The clothing materials investigated in this study had a range of different properties, the underwear being hygroscopic, hydrophilic or hydrophobic and the outerwear having different permeabilities. Intrinsic dry thermal insulation (I_{cl}) and water vapour resistance ($R_{e,cl}$) values for these materials (measured as separate textile layers using Standard No. EN 31092/ISO 11092:1993 [13]) and calculated water vapour permeability index values (i_{m}) are listed in Tables 1 and 2.

The underwear clothing consisted of two pieces with long-arm tops and long johns. The outer garments were one-piece coveralls without pockets, but with a drawstring at the waist and Velcro® ties at the wrists and ankles. For most tests all openings (at the neck, wrists and ankles) were closed. Clothing fit was kept as constant as possible.

2.2. Climates Used

The climates used in this study were ambient temperature $t_a = 10\text{ }^\circ\text{C}$ with 80% relative humidity (RH) and $t_a = 34\text{ }^\circ\text{C}$ with 18% RH. The relative humidities were chosen to ensure the same water vapour partial pressure of 1 kPa for both climates. For $t_a = 34\text{ }^\circ\text{C}$, the measurements were isothermal with the manikin surface temperature also being $34\text{ }^\circ\text{C}$ and so, as no dry heat loss and no condensation within the clothing took place, enabling the evaporative heat loss to be measured alone.

TABLE 1. Underwear Materials Used

Code	Material	Moisture Property	I_{cl} (m ² ·K/W)	$R_{e,cl}$ (m ² ·Pa/W)	i_{mt}
CO	100% cotton	hygroscopic	0.024	4.2	0.34
PES	100% polyester	hydrophilic	0.029	3.4	0.51
PP	100% polypropylene	hydrophobic	0.026	3.7	0.42

Notes. I_{cl} —intrinsic dry thermal insulation, $R_{e,cl}$ —water vapour resistance, i_{mt} —water vapour permeability index.

TABLE 2. Outerwear Materials Used

Code	Material	Moisture Property	I_{cl} (m ² ·K/W)	$R_{e,cl}$ (m ² ·Pa/W)	i_{mt}
IMP	PA webbing with outer PVC coating	impermeable	0.007	∞	0
SEMI	hydrophilic layer with outer PTFE membrane	semi-permeable	0.023	18.6	0.07
PERM	hydrophobic layer with inner PTFE membrane	permeable	0.025	5.6	0.25

Notes. I_{cl} —intrinsic dry thermal insulation, $R_{e,cl}$ —water vapour resistance, i_{mt} —water vapour permeability; PA—polyamide, PVC—polyvinyl chloride, PTFE—polytetrafluoroethylene.

2.3. Manikins Used

Results from three different thermal manikins are presented here:

- EMPA manikin (SAM) [14], 26 heated sweating sectors and 8 heated guard sectors;
- TUT (Tampere University of Technology) manikin (Coppelius) [15], 18 heated sweating sectors; and
- LU (Loughborough University) manikin (Newton) [16], 32 heated sectors.

Those manikins were used to measure the total dry heat flux of different protective clothing according to Standard No. ISO 15831:2004 [17]. Additionally, sweating resulting from a moderate-to-high workload was simulated using an integrated sweating system (EMPA and TUT manikins; sweat rate of 200 g/m²·hr) or by a pre-wetted wicking skin layer worn tightly around the manikin (LU manikin). All values of dry and wet heat loss presented here are steady-state values for the areas of the body covered by clothing only, excluding heat loss from the head, hands and feet.

3. RESULTS

The dry heat loss and the increase in heat loss caused by sweating, termed the apparent evaporative heat loss, are shown for $t_a = 10$ °C in Figures 1a and 1b respectively. For each manikin, the average dry heat loss for IMP was slightly higher than for PERM, as expected from the lower insulation values for IMP (Table 1). Comparing results from the sweating manikins at TUT and EMPA in Figures 1a and 1b, the EMPA manikin tended to give slightly lower dry heat loss but similar apparent evaporative heat loss. In spite of differing manikin designs, the relative changes in heat loss were similar for IMP clothing. Impermeable clothing gave lower apparent evaporative heat loss than permeable clothing and the increase in heat loss caused by sweating was greater for synthetic underwear (PES and PP) than for cotton (CO).

Total heat loss measured using the EMPA and LU manikins for $t_a = 10$ °C for different outerwear but the same underwear (PP) are presented in Figure 2 (with the EMPA manikin giving 175, 204 and 203 W/m² and the LU manikin giving 166, 203 and 207 W/m² for IMP, SEMI and PERM respectively). This total heat loss is broken down into dry, evaporative and additional heat loss components. In each case the dry heat loss was determined without simulating sweating. The value for actual evaporative heat

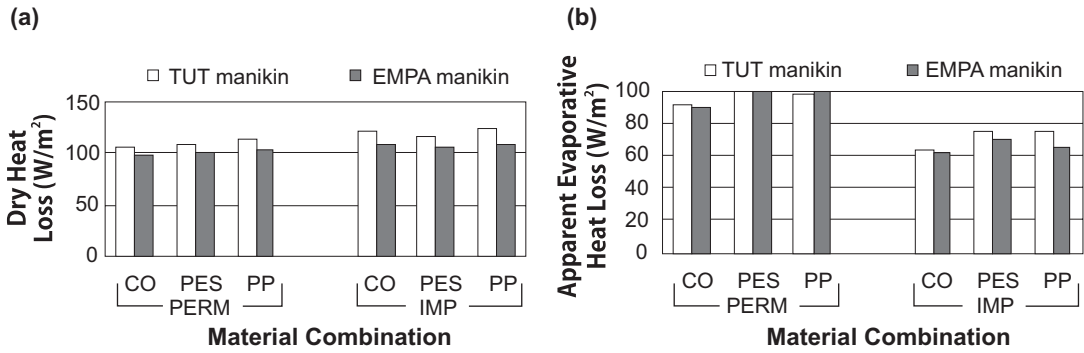


Figure 1. Results from the sweating manikins at $t_a = 10\text{ }^\circ\text{C}$; (a) dry heat loss for clothing with permeable and impermeable coveralls, (b) apparent evaporative heat loss from the increase in heat loss when sweating. Notes. CO—100% cotton, PES—100% polyester, PP—100% polypropylene. For explanation of codes PERM and IMP, see Table 2.

loss is based on results with sweating obtained for $t_a = 34\text{ }^\circ\text{C}$, which increases with clothing permeability as expected. The additional heat loss is the total heat loss minus the sum of the dry and evaporative heat loss. This additional heat loss, present for all clothing at $t_a = 10\text{ }^\circ\text{C}$, is seen to increase with water vapour resistance and accounts for as much as 34–45% of the total heat loss for IMP.

The moisture collected within the clothing layers measured using the EMPA manikin for $t_a = 10\text{ }^\circ\text{C}$ is shown in Figure 3. As expected the total moisture collected was strongly dependent on the water vapour permeability of the outer layer, with most moisture collecting in clothing with the IMP outer layer. For a given outer

layer, the moisture accumulation within the underwear was dependent on its absorptive properties, with the most moisture collecting in CO (being very hygroscopic) and the least in PP (being hydrophobic). The moisture within the tight-fitting skin on the manikin surface was dependent on the underwear layer, being least for CO and greatest for PP for a given outer layer. For the IMP results, almost all the water sweated in 2.5 hrs collected within the clothing. Some water dripped down and was collected below the manikin and some evaporated sweat (about 20% of the total 550 g sweated) could escape through the collar of the coverall which was not completely closed for these manikin tests.

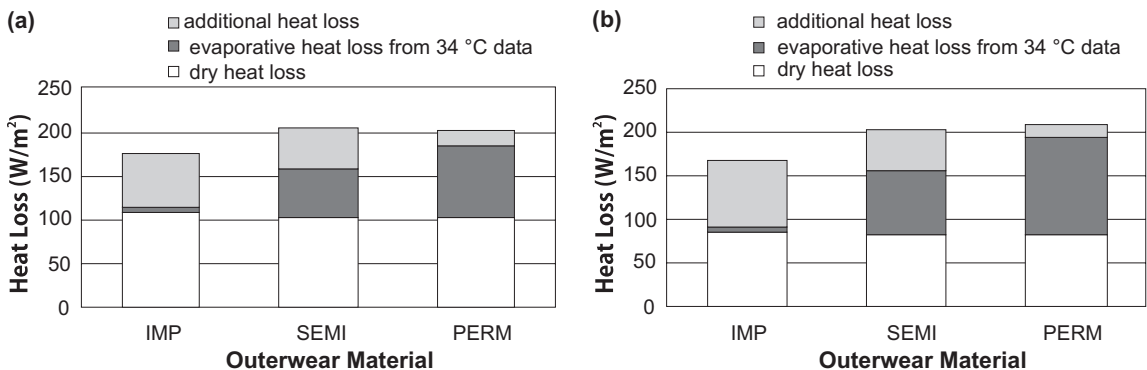


Figure 2. Total heat loss measured for $t_a = 10\text{ }^\circ\text{C}$ for different outerwear but the same underwear (PP), broken down into heat loss components (with shading as indicated in the key). Results from (a) EMPA manikin, (b) LU manikin. Notes. For explanation of codes IMP, SEMI and PERM, see Table 2.

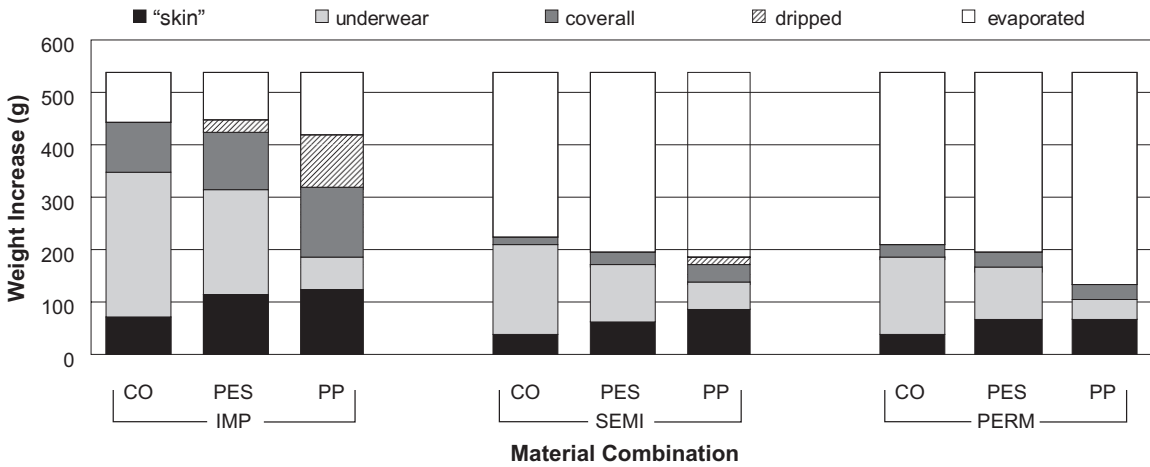


Figure 3. Moisture within the clothing layers and evaporated for $t_a = 10^\circ\text{C}$ measured using the EMPA manikin. Notes. CO—100% cotton, PES—100% polyester, PP—100% polypropylene. For explanation of codes IMP, SEMI and PERM, see Table 2.

4. DISCUSSION

Dry heat transfer occurs through conduction, radiation, convection and ventilation, whereas wet heat transfer when sweating includes several additional complex processes including evaporation, wicking, sorption and desorption, wet conduction (additional conductive heat transfer due to the clothing being wet) and condensation of moisture [12, 18]. Moisture which evaporates from the skin can either diffuse through the clothing, escape through the clothing openings in vapour form or condense within the clothing. As the total heat loss (Figure 2) was far greater than the sum of the dry and evaporative heat loss alone, one or more other processes must be responsible for the additional heat transfer observed and possible processes are considered further.

The presence of moisture within clothing can affect the heat transfer significantly, particularly if the clothing layers are saturated as evidenced by studies in both cold and hot environments, e.g., Bakkevig and Nielsen [19] and Lawson, Crown, Ackerman, et al. [20]. As the wet clothing in such studies is free to evaporate, significant heat transfer may be due to this evaporation and, without further information, it is not possible to differentiate between heat loss due to evaporation and other wet heat transfer processes involved.

Although sorption of water vapour raises the temperature of clothing locally and affects heat loss temporarily, it does not affect heat transfer when steady state is reached [2]. Similarly desorption of water shall have no effect under these conditions. Thus the additional heat loss observed here under steady-state conditions is not affected by sorption or desorption. Nevertheless, under transient conditions, sorption and desorption of moisture shall affect the total heat loss [2].

In order to quantify the amount of heat loss due to wet conduction, the conductivity of the individual layers used in the present study were measured as a function of the water content [21]. Based on those results for the clothing combination CO+IMP with the largest water content (Figure 3), the additional heat loss due to wet conduction at $t_a = 10^\circ\text{C}$ was calculated to be only 0.9 W/m^2 , which accounts for less than 2% of the additional heat loss observed. This is because the clothing layers studied here were much thinner (only ~1 mm thick) than the air layers between them and thus the intrinsic resistances of the air layers were much larger than the clothing layers [2]. Therefore for impermeable clothing combinations, wet conduction can only explain a small fraction of the additional heat loss seen.

Condensation occurs within clothing at locations where the saturated vapour pressure is reached. The build-up of moisture on the inside of the clothing layers, shown in Figure 3, is due to wicking (skin and possible underwear layer) and condensation. Wicking is a liquid transport process and does not contribute to the transfer of heat directly [10]. For the present clothing systems, a considerable amount of moisture collected within the clothing layers, particularly for the combinations with IMP. Excess condensation contained within the inner webbing of IMP, dripped down and was collected below the manikin (Figure 3). It is reasonable to assume that excess condensation dripped down from the outer layer and wetted the underwear and/or the manikin skin even before any dripping out from the clothing occurred. This may also have occurred for SEMI and possibly even for PERM. Such dripping condensation would remain within the clothing system and could then re-evaporate, thus causing further heat to be removed from the manikin.

Under cold conditions condensation causes the inner surface of an impermeable outer clothing layer to heat up by several degrees [1, 2]. Such increases in inner surface temperature were observed for the overalls measured here (up to 4.5 °C for IMP and up to 3.3 °C for SEMI). As the underwear and outer layers were mainly separated by air, apart from contact areas at the shoulders and closed openings, almost all of the moisture within the outer layer is assumed to be due to evaporation from the skin and underwear condensing on the inside of the outer layer. For IMP, assuming that all of the 103–132 g of moisture which collected in the outer layer was due to condensation and all of the heat generated by this condensation was lost to the environment over the 2.5 hrs of simulated sweating, 55–72% of the additional heat loss would be accounted for. However, some of this heat was used to heat up the outer layer. This suggests that much more condensation took place than the moisture collected in the outer layer, which would confirm the hypothesis that some of the outer layer condensation dripped back down onto the manikin skin and underwear

layers and evaporated again (thus drawing more heat from the manikin) and then recondensed on the outer layer in a cyclic manner. Furthermore, such a cyclic process would account for the large increases in the outer layer temperature observed. Heating up of the outer layer increased the temperature gradient between this layer and the environment and enabled heat to be lost to the environment more efficiently.

Consequently, the only two processes which can be identified as being responsible for the additional heat loss observed are condensation and an increase in conduction of the clothing, with the former involving a cycle of evaporation and condensation of moisture which remains within the clothing and heats up the outer layer and accounts for almost all of the additional heat loss for impermeable clothing. Other work [22] has shown that condensation increases with decreasing temperature. Therefore the additional heat loss due to condensation and wet conduction should also increase when the air temperature is reduced. This has been confirmed by a more recent study [23].

Preliminary results from the EMPA manikin have been presented previously [24], where the evaporative heat loss was estimated from the mass loss of evaporation by assuming that all evaporative cooling removes heat from the body. However, depending on the location, as some of the evaporative cooling may remove heat from the clothing [1], measuring the evaporative heat loss directly at 34 °C, as in this paper, is considered to be the more accurate method of determining evaporative heat loss.

An interlaboratory study of six sweating thermal manikins [25] (including the TUT and EMPA manikins but excluding the LU manikin) showed that such manikins tend to give limited reproducibility due to different manikin designs and experimental techniques. Thus it is to be expected that comparing the heat loss values of different manikins here, which indeed used different experimental techniques and included the characteristics of each manikin, shall give different results. The differences between the results for the TUT and EMPA manikins presented here are 7–11% for dry heat loss in

Figure 1a and up to 13% for apparent evaporative heat loss in Figure 1b. Differences between the EMPA and LU manikins are somewhat higher. In Figure 2, the LU manikin gives on average 23% lower dry heat loss than the EMPA manikin but 24 and 34% higher evaporative heat loss for SEMI and PERM respectively. In spite of these differences in heat loss measured using different manikins, by considering the results for each manikin alone, general trends of changes in total and evaporative heat loss with the properties of the clothing are clearly seen.

5. CONCLUSIONS

Contrary to present standards for predicting thermal stress, dry and evaporative heat loss are found not to be the only heat loss processes when performing moderate to high workloads in the cold (for $t_a = 10^\circ\text{C}$). Additional heat loss increases with decreasing permeability, becoming up to 45% of the total heat loss for impermeable clothing. Under steady-state conditions, this additional heat loss is attributable to a cycle of evaporation and condensation of moisture which remains within the clothing and removes heat from the skin, heats up the outer layer and releases heat into the environment and into the increased (wet) conductivities of the clothing layers. Under transient conditions, sorption and desorption of moisture shall also affect the heat loss. Thus, depending on the permeability of the clothing, the total heat loss under cold conditions can be much higher than expected from the sum of dry and evaporative heat loss and this fact shall need to be considered in future standards which consider heat transfer through clothing.

REFERENCES

- Lotens WA, Vandelinde FJG, Havenith G. Effects of condensation in clothing on heat-transfer. *Ergonomics*. 1995;38(6):1114–31.
- Farnworth B. A numerical-model of the combined diffusion of heat and water-vapor through clothing. *Text Res J*. 1986;56(11): 653–65.
- Spencer-Smith JL. The physical basis of clothing comfort, part 4: the passage of heat and water through damp clothing assemblies. *Clothing Research Journal*. 1977;5:116–28.
- Cheung SS, McLellan TM, Tenaglia S. The thermophysiology of uncompensable heat stress—physiological manipulations and individual characteristics. *Sports Medicine*. 2000;29(5):329–59.
- Parsons KC. *Human thermal environments*. London, UK: Taylor & Francis; 2003.
- Malchaire J, Piette A, Kampmann B, Mehnert P, Gebhardt H, Havenith G, et al. Development and validation of the predicted heat strain model. *Ann Occup Hyg*. 2001;45(2):123–35.
- Holmér I. Protective clothing and heat stress. *Ergonomics*. 1995;38(1):166–82.
- Li Y, Zhu QY. A model of coupled liquid moisture and heat transfer in porous textiles with consideration of gravity. *Numerical Heat Transfer. Part A, Applications*. 2003; 43(5):501–23.
- Gibson PW, Charmchi M. Coupled heat and mass transfer through hygroscopic porous materials: application to clothing layers. *Sen-I Gakkaishi*. 1997;53(5):183–94.
- Fan J, Cheng X, Wen X, Sun W. An improved model of heat and moisture transfer with phase change and mobile condensates in fibrous insulation and comparison with experimental results. *International Journal of Heat and Mass Transfer*. 2004;47(10–11):2343–52.
- Blatteis C, Boulant J, Cabanac M, Cannon B, Freedman R, Gordon, et al. Glossary of terms for thermal physiology. *Jpn J Physiol*. 2001;51(2):245–80.
- Havenith G, Holmér I, Mainander H, den Hartog E, Richards MGM, Bröde P, et al. Assessment of thermal properties of protective clothing and their use. Final THERMPROTECT Technical Report, European Union Contract G6RD-CT-2002-00846; 2005.
- European Committee for Standardization (CEN). Textiles—determination of physiological properties—measurement of thermal and water-vapour resistance under steady state conditions (sweating guarded-hotplate

- test) (ISO 11092:1993) (Standard No. EN 31092:1993). Brussels, Belgium: CEN; 1993.
14. Richards MGM, Mattle NG. A Sweating agile thermal manikin (SAM) developed to test complete clothing systems under normal and extreme conditions. In: Human Factors and Medicine Panel Symposium—Blowing Hot and Cold: Protecting Against Climatic Extremes. Dresden, Germany: RTO/NATO; 2001. p. 1–7.
 15. Meinander H. Coppelius—a sweating thermal manikin for the assessment of functional clothing. In: Proceedings of the 4th Scandinavian Symposium on Protective Clothing Against Chemicals and Other Health Hazards (Nokobetef IV). Kittilä, Finland: Finnish Institute of Occupational Health; 1992. p. 157–61.
 16. Havenith G, Wang X and THERMPROTECT network. Evaporative cooling in protective clothing. In: 3rd European Conference on Protective Clothing (ECPC) and NOKOBETEF 8. Protective Clothing Towards Balanced Protection [CD-ROM]. Warszawa, Poland: Central Institute for Labour Protection – National Research Institute; 2006.
 17. International Organization for Standardization (ISO). Clothing—physiological effects—measurement of thermal insulation by means of a thermal manikin (Standard No. ISO 15831:2004). Geneva, Switzerland: ISO; 2004.
 18. Lotens WA. Heat transfer from humans wearing clothing. Soesterberg, The Netherlands: TNO Institute for Perception; 1993.
 19. Bakkevig MK, Nielsen R. Impact of wet underwear on thermoregulatory responses and thermal comfort in the cold. *Ergonomics*. 1994;37(8):1375–89.
 20. Lawson LK, Crown EM, Ackerman MY, Dale JD. Moisture effects in heat transfer through clothing systems for wildland firefighters. *International Journal of Occupational Safety and Ergonomics (JOSE)*. 2004;10(3):227–38.
 21. Richards MGM. Study of materials to investigate the effects of moisture on the heat transfer through protective clothing. Report on Project THERMPROTECT, European Union Contract G6RD-CT-2002-00846; 2004.
 22. Rossi RM, Gross R, May M. Water vapour transfer and condensation effects in multilayer textile combinations. *Text Res J*. 2004;74(1):1–6.
 23. Havenith G, Richards MGM, Wang X, Bröde P, Candas V, den Hartog E, et al. Apparent latent heat of evaporation from clothing: attenuation and “heat pipe” effects. *J Appl Physiol*. 2008;104:142–9.
 24. Richards MGM, Broede P, Candas V, den Hartog E, Havenith G, Holmér I, et al. Effects of moisture on the heat transfer through protective clothing. In: Proceedings of the International Conference on Environmental Ergonomics [CD-ROM]. Ystad, Sweden; 2005.
 25. Richards MGM, McCullough EA. Revised interlaboratory study of sweating thermal manikins including results from the sweating agile thermal manikin. *Journal of ASTM International*. 2005;2(4):27–39.