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Apparent latent heat of evaporation from clothing: attenuation and "heat pipe" effects

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Havenith G, Richards MG, Wang X, Bröde P, Candas V, den Hartog E, Holmér I, Kuklane K, Meinander H, Nocker W. Apparent latent heat of evaporation from clothing: attenuation and "heat pipe" effects. *J Appl Physiol* 104: 142–149, 2008. First published October 18, 2007; doi:10.1152/japplphysiol.00612.2007.—Investigating claims that a clothed person's mass loss does not always represent their evaporative heat loss (EVAP), a thermal manikin study was performed measuring heat balance components in more detail than human studies would permit. Using clothing with different levels of vapor permeability and measuring heat losses from skin controlled at 34°C in ambient temperatures of 10, 20, and 34°C with constant vapor pressure (1 kPa), additional heat losses from wet skin compared with dry skin were analyzed. EVAP based on mass loss (E_{mass}) measurement and direct measurement of the extra heat loss by the manikin due to wet skin (E_{app}) were compared. A clear discrepancy was observed. E_{mass} overestimated E_{app} in warm environments, and both under and overestimations were observed in cool environments, depending on the clothing vapor permeability. At 34°C, apparent latent heat (λ_{app}) of pure evaporative cooling was lower than the physical value (λ; 2,430 J/g) and reduced with increasing vapor resistance up to 45%. At lower temperatures, λ_{app} increases due to additional skin heat loss via evaporation of moisture that condenses inside the clothing, analogous to a heat pipe. For impermeable clothing, λ_{app} even exceeds λ by four times that value at 10°C. These findings demonstrate that the traditional way of calculating evaporative heat loss of a clothed person can lead to substantial errors, especially for clothing with low permeability, which can be positive or negative, depending on the climate and clothing type. The model presented explains human subject data on EVAP that previously seemed contradictive.

heat balance; sweat evaporation; condensation; protective clothing; evaporative cooling efficiency

EVAPORATION OF MOISTURE, usually sweat, is crucial in human thermoregulatory function. It provides cooling where otherwise body heat losses would not be able to match metabolic heat generation. The traditional method to determine the rate of evaporative heat loss in humans and animals is to determine the mass change of the (clothed) body per unit of time, corrected for the rates of respiratory moisture loss and metabolic mass losses. This mass change rate is then multiplied by the latent heat of evaporation (λ; J/g) (15) to calculate the rate of energy lost by evaporation. When moisture evaporates from the skin of a person wearing clothing and travels toward the environment, several different moisture transport processes may be involved. The moisture may be sorbed and subsequently desorbed by textile fibers, it may condense in outer layers if these are colder than the skin, it may be ventilated from the clothing microclimate, or finally it may diffuse through the outer clothing layer (3, 10, 11, 12, 13, 30, 34). It is mostly assumed that only moisture vapor that actually leaves the clothing ensemble contributes to body cooling, and hence evaporative heat loss is typically calculated from the mass change of the human-clothing system rather than from the mass change of the nude person within the clothing system.

Most thermophysiological and clothing-related research on exchanges of heat and mass between humans (or animals) and their thermal environment is based on heat balance analysis, which determines the various avenues for heat generation and heat transfer: metabolic rate (M), external work (W), radiation (R), convection (C), conduction (K), evaporation (EVAP), respiratory heat losses (RESP), and finally heat storage (S) in the body. Most of these parameters, normally expressed as rates (in Watts), can be determined directly, whereas the dry (DRY) heat loss rate (R + C + K) is normally calculated as the balance of all other heat gain and loss rates (DRY = M − W − EVAP − RESP − S). The latter is often done in clothing research and thermal tolerance studies (17, 19, 20, 31), where the DRY value is used to calculate the thermal insulation of the clothing, and EVAP is used to calculate the clothing vapor resistance. It should be noted that any errors made in the determination of one of the heat balance parameters will end up accumulated in the value for DRY. This could only be avoided if DRY leaving the skin is measured directly. However, with current technology, this is not possible on clothed humans while sweating (7, 8), with measurements in a calorimeter providing the closest approximation.

Based on the moisture transport processes in clothing as discussed above, several authors have suggested that the calculation of evaporative heat loss from the clothed mass loss may not always be correct (7, 8, 22, 29, 31). Lotens et al. (29) demonstrated that for impermeable clothing (classic rainwear or chemical protective clothing) worn in a cool environment, the heat balance determined in the standard manner did not add up, producing unrealistically high values for dry heat loss.

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They suggested that in that condition the evaporative cooling of the human body when calculated from clothed mass loss may be underestimated. Furthermore, it was demonstrated that this error was not present for impermeable clothing when plastic foil was wrapped over the skin, which did not affect the mass change of the clothed person but did prevent evaporation from the skin. Havenith and Lotens (22) observed a similar effect when testing semi-permeable vs. impermeable rainwear in a cool environment, showing that total heat loss rates in both garments were much closer than expected based on tests in a warm climate. Both papers suggested that condensation on the inside of the outer clothing layer of sweat evaporated from the skin, releasing heat at the clothing surface without the moisture leaving the clothing, may be responsible for the underestimation of evaporative heat loss rate when deducting this from clothed mass loss rate. On the other hand, Craig and Moffit (8) and McLellan et al. (31), while testing protective clothing in warm environments, also observed inconsistencies in the heat balance calculation results, suggesting that, in their case, evaporative heat transfer rate may be overestimated when based on clothed mass loss rate.

A conceptual model for the different heat transfer pathways in the case of wetted skin is shown in Fig. 1. For a certain clothing and climatic condition, rates of ventilation (A) and basic dry heat loss (B) are assumed constant. The added heat loss when the skin is wet is then attributed to evaporation out of the clothing to the environment (E), extra conduction in the fabrics due to moisture (C), and evaporation of moisture at the skin that recondenses in and releases heat to the outer clothing layers (D) without evaporating to the environment, as suggested earlier (22, 29). The latter pathway (D) will be referred to as the "microclimate heat pipe," using the analogy that heat is transported by vapor and released further out by condensation. Contrary to a conventional heat pipe, in the case of clothing, there may be no or little recirculation of the liquid (i.e., an open circuit) but rather a continuous fresh supply by the sweat glands. A possible recirculation of liquid from the outer layer to the skin is only expected when the garments get saturated. Garments will take up moisture by wicking liquid from the skin (F) or when moisture condenses on its way to the outer layers (D).

Based on this model, it is hypothesized that the discrepancies observed in the heat (8, 31) and cold (22, 29) may be attributed to *1*) the effect of temperature on pathway D (condensation); *2*) a difference in the relation between evaporative heat loss rate (E) and mass loss rate when clothing is worn compared with nude, which would imply that the effective value for latent heat of evaporation is different when wearing clothing; *3*) the interaction of the microclimate heat pipe effect with the permeability level of the clothing worn. This study will test all three issues by varying temperature and clothing permeability to study their impact on clothing heat transfer pathways. To avoid the technical limitations mentioned above and the inherently large "noise" (24) in conventional heat balance measurements on humans, individual heat loss components were measured using a thermal manikin.

METHODS

Manikin

To discriminate between and determine all heat exchanges, measurements were made using a thermal manikin (Newton, MTNW, Seattle, WA) shown in Fig. 2. This manikin has 32 zones for which the surface temperature can be controlled independently, and the total heat input required to achieve this was accurately measured. This heat input is a direct measure of the heat loss from the manikin. This measurement and the calibration of the manikin are described extensively in ISO 15831:2004 (26) and ASTM F1291-05 (1). To provide an evaporative surface, the skin consisted of a thin stretch cotton layer, on top of the heating layer, that was wetted before dressing and acted as a "sweating skin layer" (2). Continued wettedness of the skin layer was monitored for all individual zones via their heat loss rate, which dropped sharply when a zone started to dry out. Apart from heat losses, also the mass change rate of the clothed, wet manikin was determined by continuous weighing (0.1 Hz) of the whole setup

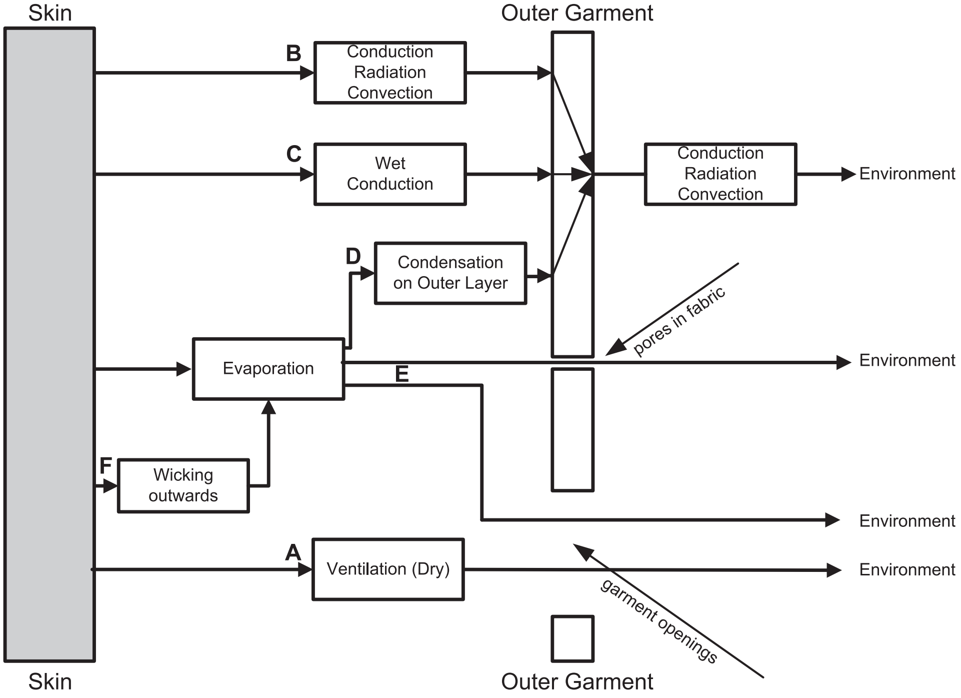

Fig. 1. Schematic representation of heat transfer pathways when skin is wetted. Modified from Ref. 18.

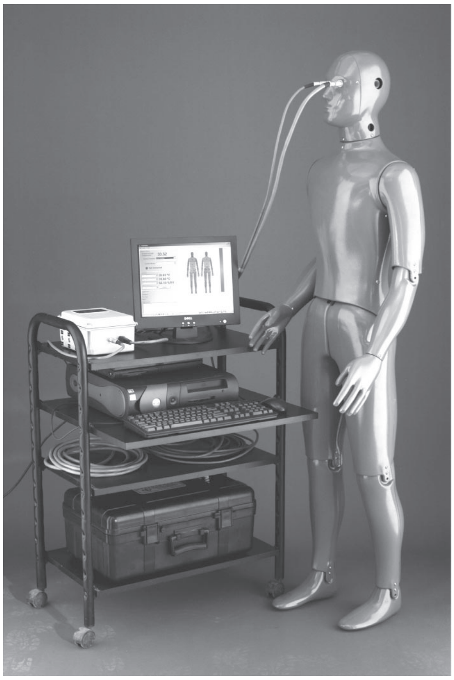

Fig. 2. Thermal manikin “Newton” (MTNW, Seattle, WA).

(Sartorius balance 150 kg, precision 1 g; absolute accuracy to ±5 g). This allowed continuous determination of the rate of water evaporation from the clothing system and thus of the real evaporative mass loss rate from the clothing system. The manikin was placed in front of three fans that were mounted in a vertical plane, which produced the reference wind speed of 0.5 m/s.

Since this paper intends to study the effect of clothing, all measurements and data in this paper are calculated for the clothed area only. Data from head, hands, and feet are excluded.

Clothing

Three custom-made outer garments were used (Fig. 3), identical in design and production, but of either impermeable (IMP), semipermeable (SEMI), or permeable (PERM) material, providing three levels of vapor permeability (Table 1). Although not essential to the testing, an attempt was made to match the materials for heat resistance, but this was not achieved for the IMP material. These outer layers were tested in combination with three representative underwear types of similar design [cotton (Gnägi), polyester, and polypropylene (Table 1)] selected to give a similar material heat and vapor resistance. Data for different underwear types will be lumped together in the analysis.

Climate

Experimental conditions were chosen to enable determination of real and “apparent” evaporative cooling efficiency. All climates had the same water vapor pressure (1 kPa), so that the driving force (vapor pressure gradient) for evaporation was the same in all tests, and thus for a certain suit (fixed evaporative resistance) the evaporative moisture loss should be the same for all temperatures. For ambient temperature, three levels were chosen: 34°C (isothermal conditions where skin temperature = ambient temperature, and thus no dry heat loss is present), 20°C, and 10°C. The chosen 1-kPa vapor pressure, when combined with these temperatures, resulted in relative humidities of 18.5, 42, and 80% for 34, 20, and 10°C, respectively.

Calculations and Definition of Terms

In terms of heat losses, with a dry skin, only dry heat loss is present (pathways A and B in Fig. 1), whereas with a wet skin at 34 °C only evaporative heat loss (pathway E) is present. At lower temperatures, both evaporative and dry heat loss are present simultaneously, with the latter increasing with the temperature gradient between skin and environment. Combining the results from these conditions allows the following calculations (all heat losses are expressed as rates).

Real dry heat loss. Real dry heat loss ($\mathrm{DRY_{real}}$) is defined as the heat loss measured on dry manikin at 10, 20, and 34°C.

Apparent evaporative heat loss. Apparent evaporative heat loss (E_{app}) is the increase in heat loss compared with dry when the manikin skin is wet (i.e., heat loss of wet manikin − heat loss of dry manikin; at same temperature). This is referred to as “apparent” as apart from evaporation (pathway E); it also includes heat loss due to wet conduction and evaporation-condensation (pathways C and D).That is, it includes all changes in heat loss due to the wet skin.

$$E_{\mathrm{app}}\ (\mathrm{W/m^2}) = \text{total manikin heat loss when wet} - \mathrm{DRY_{real}} \qquad (1)$$

For measurements at 34°C, dry heat loss, convective heat loss, as well as any conductive heat losses are zero, and no condensation can take place in the clothing. Thus, in that case, *Eq. 1* represents solely the actual evaporation to the environment (pathway E).

Real evaporative heat loss. Real evaporative heat loss (E_{real}), meaning the heat loss of the manikin when the skin is wet, measured at 34°C (pathway E only) was

$$E_{\mathrm{real}}\ (\mathrm{W/m^2}) = E_{\mathrm{app}}\ (\text{at } 34^\circ\mathrm{C}) = \text{total wet manikin heat loss at } 34^\circ\mathrm{C} \qquad (2)$$

The common way to determine evaporative heat loss in human experiments is to calculate it from the latent heat of evaporation of all mass that is lost from the clothed person (corrected for metabolic and respiratory mass changes). In the present testing, this same value is determined by the mass loss rate of the clothed manikin as evaporative cooling potential (E_{mass}), which is the calculated latent heat content of the moisture that is evaporating from the ensemble (the “human-clothing-system”) (15) as measured by the mass loss rate on the Sartorius scale:

$$E_{\mathrm{mass}}\ (\mathrm{W/m^2}) = \text{mass loss rate}\ (\mathrm{g \cdot m^{-2} \cdot s^{-1}}) \cdot \lambda (\mathrm{J \cdot g^{-1}}) \qquad (3)$$

where

$$\lambda = \text{enthalpy of evaporation (J/g)} = 0.001\ [2.792 \cdot 10^6 - 160 \cdot T - 3.43 \cdot T^2\ (\text{with } T \text{ in } K)] \approx 2{,}430 \text{ at } 30^\circ\mathrm{C}\ (15) \qquad (4)$$

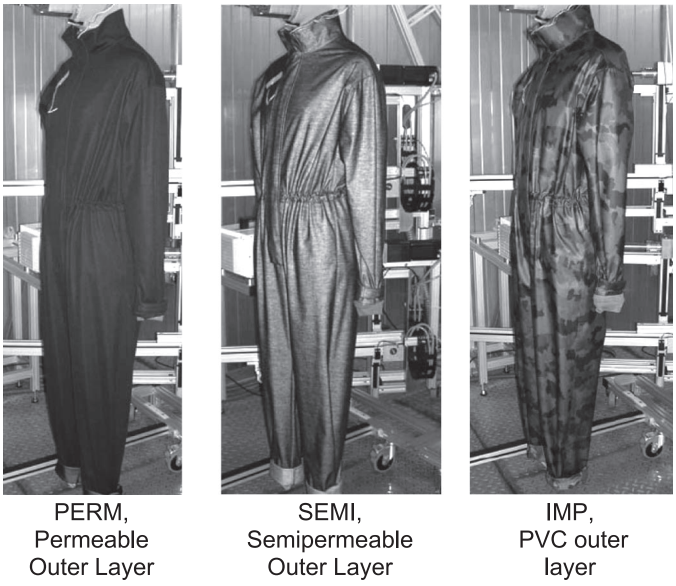

Fig. 3. The outer clothing layers used. (Photographs are from EMPA.)

Table 1. *Underwear and outer layer materials characteristics*

Code	Material	Moisture Property	R_{ct}, $m^2 \cdot K/W$	$R_{e,cl}$, $m^2 \cdot Pa/W$	i_m, nd	AP, $l \cdot m^{-2} \cdot s^{-1}$	f_{cl}, nd
Underwear							
CO	100% cotton	Hygroscopic	0.024	4.2	0.34	NM	NM
PES	100% polyester	Hydrophilic	0.029	3.4	0.51	NM	NM
PP	100% polypropylene	Hydrophobic	0.026	3.7	0.42	NM	NM
Outerwear							
IMP	PA webbing with outer PVC coating	Impermeable	0.007	∞	0	0.24	1.324
SEMI	Hydrophilic layer with outer PTFE membrane	Semi-permeable	0.023	18.6	0.07	1.98	1.285
PERM	Hydrophobic layer with inner PTFE membrane	Permeable	0.025	5.6	0.25	1.02	1.284

Fabric heat resistance (R_{ct}) and vapor resistance ($R_{e,cl}$) are measured on a sweating hot plate (ISO 11092). Air permeability (AP) is measured according to EN ISO 9237:1995. CO, cotton; PES, polyester; PP, polypropylene; IMP, impermeable; SEMI, semi-permiable; PERM, permeable; NM, not measured; f_{cl}, the clothing surface area factor (ISO 9920) of the fully clothed manikin; i_m, clothing vapor permeability index; nd, nondimensional.

With these data available, the apparent and potential, and the real and potential evaporative heat losses can be compared, and the evaporative cooling efficiency calculated.

Apparent evaporative cooling efficiency. The apparent evaporative cooling efficiency (η_{app}) is the apparent evaporative heat loss of the wet manikin divided by the evaporative cooling potential under the same temperature condition.

$$\eta_{app} = \frac{\text{apparent evaporative heat loss of wet manikin}}{\text{evaporative cooling potential}} = \frac{E_{app}}{E_{mass}} \quad (5)$$

Real evaporative cooling efficiency of the body. Real evaporative cooling efficiency of the body (η_{real}) is the real evaporative heat loss from the skin (at 34°C) divided by the evaporative cooling potential in a given condition:

$$\eta_{real} = \frac{\text{real EVAP (at 34°C)}}{\text{evaporative cooling potential}} = \frac{E_{real}}{E_{mass}} = \eta_{app} \text{ (at 34°C)} \quad (6)$$

And finally, these results for evaporative cooling efficiency can be interpreted in terms of the observed latent heat of evaporation that benefits the body when clothing is worn. If evaporative cooling efficiency is 1.0, the latent heat observed is equal to the theoretical value, whereas it may be lower if not all latent heat for the observed mass loss is taken from the body or higher if more heat is lost than theoretically expected based on the mass loss.

Apparent latent heat of evaporation. Apparent latent heat of evaporation (λ_{app}) is the measured energy released from the manikin surface divided by the observed evaporation rate from the clothed body

$$\lambda_{app} \text{ (J/g)} = \frac{\text{apparent evaporative heat loss of wet manikin (W/m}^2)}{\text{mass loss rate (g} \cdot \text{m}^{-2} \cdot \text{s}^{-1})} = \frac{E_{app}}{\text{dMass/d}t} \quad (7)$$

As the temperature of the outer wet skin surface decreased slightly below the setpoint value due to the evaporative cooling in some conditions, all evaporative heat losses were corrected for the dry heat loss component caused by any surface temperature decreases observed.

Test Preparation and Protocol

Once the internal and surface temperatures of the manikin had stabilized, the data acquisition started. For the wet experiments, the "skin" was wetted at this point with distilled water until fully wet, while no dripping was observed. Then, for both dry and wet tests, the manikin was dressed with underwear and outerwear. The average heat flux was seen to stabilize within 20 min after wetting. After 40 min, the test was terminated, and all clothing was weighed again. In the wet tests, the mass loss (pathway E in Fig. 1) was registered (0.1 Hz) by the Sartorius scale. Mass loss rate was calculated from the slope of this curve for the time period when mass loss rate and heat loss rate were both found to be stable. Additionally, all clothing used was weighed before and after testing.

The parameters listed above were determined in a steady-state condition of the boundary conditions (skin wettedness). It should be noted that, in human exposures to heat and cold, these boundary conditions may not be stable for the initial period where sweating starts and clothing starts to absorb moisture. Hence, the results obtained here may be different for this initial period if this shows strong transients in boundary conditions. Once the skin is wet, however, the results of this study should apply, even if body temperatures are still transient.

Statistics

Dependent variables (derived from above equations) were analyzed by a two-way ANOVA, with clothing permeability (3 levels) and temperature (3 levels) as independent factors. Since data were lumped over the three underwear types, with typically one replication (1, 2, 24), there were six datapoints per condition. Differences between individual conditions were tested by a Tukey's post hoc test for relevant comparisons. Apparent evaporative cooling efficiency values were tested for deviation from unity using single sample *t*-tests. Statistical testing was performed using SYSTAT (SYSTAT version 11). $P < 0.05$ was taken as significant.

RESULTS

Results for the different heat loss components for the different underwear types showed only minor differences and are merged per outerwear type in the following graphs. In Fig. 4, the total manikin heat loss is shown for the different test conditions. The breakdown of the total value in its components will be discussed below. Total heat loss is significantly affected by both permeability and temperature, and these interact (all $P < 0.001$). At each temperature, all suits differ significantly, except for SEMI and PERM at 10 and 20°C, whereas each suit has a significantly different heat loss between temperatures.

Breakdown of Heat Loss in Components

For all test climates that had the same vapor pressure, it was assumed that the vapor loss would be similar in all conditions for any specific clothing configuration. The results confirm that this was the case. Correlations of mass losses for all clothing types compared for the different temperatures produced an *r* of 0.98. In addition, repeated-measures ANOVA did not show any significant temperature effect on mass loss. This is also visible in the data for E_{mass} calculated from the mass changes

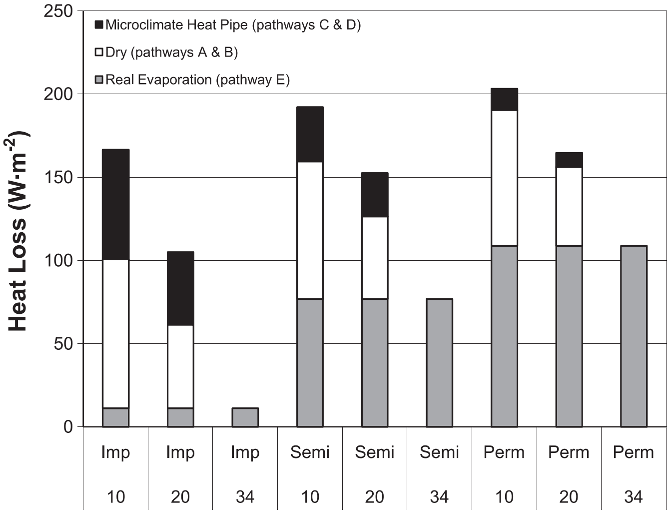

Fig. 4. Total heat loss of the wet manikin for all outer garments broken down in its components. Real evaporative heat loss from skin is deducted from the value at 34°C, as discussed in text. Microclimate heat pipe heat loss results from combined heat loss due to increased conduction and the microclimate evaporation-condensation process (pathways C and D in Fig. 1).

of the manikin (Fig. 5, solid lines, based on *Eq. 3*). One can see that this is related to the material's vapor permeability ($P < 0.001$), according to expectations, but shows no significant dependence on temperature nor any interaction of temperature and permeability. Since the vapor pressure gradient between the skin and environment was held constant at the different temperatures, similar values were observed for each suit in the three temperatures, as expected.

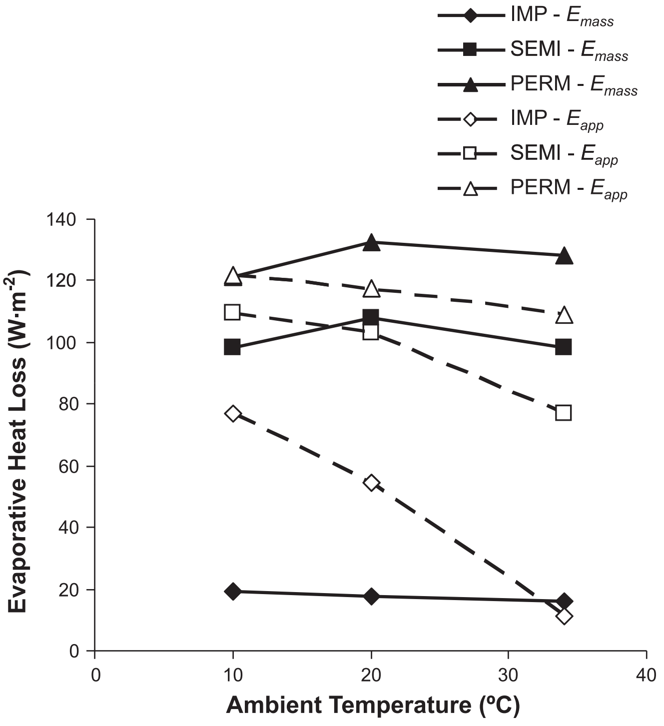

Fig. 5. Measured apparent evaporative heat loss (E_{app}, according to *Eq. 1*) and evaporative heat loss potential (E_{mass}) calculated from the mass change per unit of time.

Figure 5 also shows the E_{app} (broken lines), i.e., the sum of pathways C, D, and E (see *Eq. 1*). Despite finding similar mass losses and thus similar E_{mass} from each suit for the different temperatures, the calculated apparent evaporative heat loss increases with lowering temperature ($P < 0.001$), although for PERM this is not significant. Temperature and permeability interact significantly ($P < 0.001$), with the temperature effect being larger the lower the permeability.

The differences between the solid and broken lines in Fig. 5 show the discrepancy between E_{app} and E_{mass}, i.e., the difference between heat loss measured and heat loss calculated from mass loss. It is evident that the impermeable suit mainly gives higher heat losses than expected, whereas the permeable suits also show less heat loss than expected at the higher temperatures. All measured values at 34°C are less than expected from mass loss ($P < 0.05$).

Since it is assumed that the real evaporative heat loss rate is equal at all temperatures (same ambient vapor pressure of 1 kPa), it is possible to use the heat loss value measured at 34°C as a reference condition where *1*) no condensation can take place and *2*) heat loss through conduction is absent (or in the worst case minimal and directed toward the body if the skin would cool down slightly below 34°C). Thus, if this E_{real} (pathway E; *Eq. 2*) is subtracted from the total wet heat loss (pathways C, D, and E) measured using the manikin (E_{app}), the combined heat transfer caused by an increase in conduction and the microclimate heat pipe system (pathways C and D) can be deduced.

The values of the different components of the total manikin heat loss are summarized in Fig. 4. All suits show some additional heat loss through the conduction + microclimate heat pipe avenues for temperatures below 34°C. This additional heat loss increases with decreasing temperature ($P < 0.001$, although for PERM this is not significant between 10 and 20°C) as well as with increasing water vapor resistance ($P < 0.001$), and these interact ($P < 0.001$). The percentage heat losses (Fig. 6) show that the percentage contribution of the wet conductive + microclimate heat pipe heat loss to total heat loss is similar for both 10 and 20°C for a given suit. This heat loss for the present conditions can be described as linear

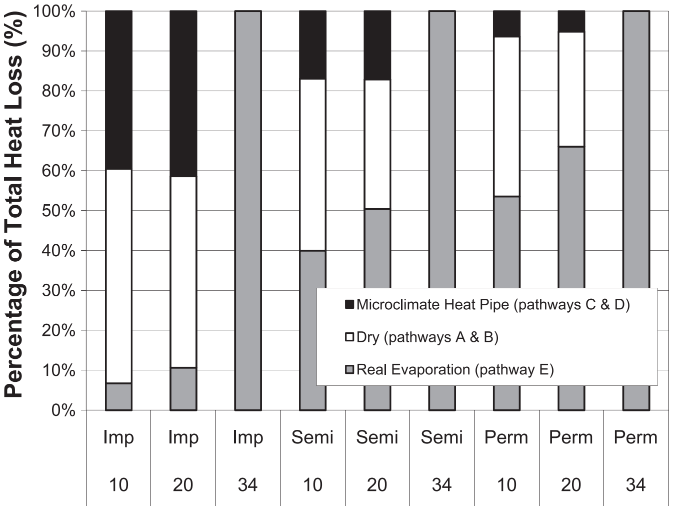

Fig. 6. Individual components of total heat loss for all outer garments as percentage of total heat loss. See Fig. 4 for details.

functions of the skin-environment temperature gradient: for IMP pathways C + D heat loss (W/m^2) = 2.75($T_{sk} - T_a$) ($r^2 = 0.96$); Semi: = 1.66($T_{sk} - T_a$) ($r^2 = 0.88$); Perm = 0.40($T_{sk} - T_a$) ($r^2 = 0.40$), where T_{sk} is skin temperature and T_a is ambient temperature.

Real and Apparent Evaporative Cooling Efficiency

Figure 7 shows the "apparent evaporative cooling efficiency" (*Eq. 5*) and the related "apparent latent heat of evaporation" (*Eq. 7*). At present, in all experimental research, the cooling efficiency is assumed to be equal to unity and λ_{app} equal to 2,430 J/g. For the impermeable suit, at lower temperatures, η_{app} became much greater than 1.0, and thus λ_{app} exceeds λ. Thus more heat is lost than expected based on the mass loss of the person-clothing system. For the more permeable suits, η_{app} remains ~1.0 (low temperatures) or lower, indicating that heat loss is equal to or less than that expected based on mass loss. For all suits, η_{app} at 34°C is significantly lower than 1.0 ($P < 0.001$), and thus λ_{app} is lower than λ.

Figure 8 shows the real evaporative cooling efficiency (η_{real}, *Eq. 6*), i.e., the calculation of efficiency with contributions of the microclimate heat pipe excluded (purely pathway E in Fig. 1). Here, we see a more constant evaporative cooling efficiency over the temperature range, although the temperature effect is still significant ($P < 0.01$), mainly for IMP. η_{real} differs with vapor permeability of the outer garment ($P < 0.001$), and temperature and permeability show an interaction ($P < 0.05$). Furthermore, all values are significantly lower than one ($P < 0.001$), indicating that not all evaporative heat is taken from the skin.

Heat Pipe Loss vs. Mass Gain of Clothing

Over all tests, clothing gained on average 200 g (standard deviation = 92 g) in mass. The amount of heat transported through evaporation-condensation did not correlate well with the mass gain of the clothing (underwear + outer clothing). r^2 Values were lower than 0.15 over all data, and also when the relation was studied per temperature level this did not improve. However, when the cotton underwear tests were excluded, the r^2 increased to 0.63. For the different temperature levels, r^2 became 0.46 at 20°C and 0.54 at 10°C with cotton excluded.

DISCUSSION

In the total manikin heat loss (Fig. 4), a clear effect of the temperature gradient between skin and environment is evident, as is the effect of the outer garment vapor permeability. The heat loss ranking is consistent with the outer layer ranking for vapor resistance shown in Table 1. The expectation would have been that E_{app} (broken line in Fig. 5) for each suit remain constant over temperature, as the vapor pressure of the environment and skin was kept the same (1 kPa) (or, in case skin surface temperature would drop slightly at lower temperature, evaporation should be less at low temperature due to a reduced vapor pressure gradient). However, this is evidently not the case for E_{app}. On the other hand, E_{mass}, although also related to the material's vapor permeability, does not show the negative relation with temperature, and thus this does behave exactly as expected.

A comparison of the two sets of lines in Fig. 5 clearly shows that there is a substantial discrepancy between E_{app} and E_{mass} going in two directions: for the higher temperatures, wet heat loss is lower than expected based on mass loss, whereas at lower temperatures, with lower permeabilities of the clothing, heat loss is higher than expected based on mass loss. This confirms earlier, seemingly conflicting, observations by Lotens et al. (29), Havenith and Lotens (22), and McLellan et al. (31). The present observations are illustrated in Fig. 7 and Fig. 8, where the ratio between the observed heat loss and the latent heat of the observed mass loss is presented. This ratio can be seen as the apparent evaporative cooling efficiency of the body (*Eq. 5*). So, assuming the physical latent heat of evaporation is constant, this ratio shows which fraction of this latent heat is actually taken from the body, with the remainder taken from the microclimate environment. Figure 8 shows how much of the heat of the actual evaporation through the clothing is taken from the body. All of the observations for η_{real} are below 1.0, showing that, when wearing clothing, the effective cooling of the body is less than expected based on the latent heat of the evaporated water. The lower the permeability of the clothing, the lower the real evaporative efficiency and λ_{app} for pure evaporative heat loss. This observation supports earlier suggestions (5, 8) that wicking of moisture into the clothing layers (pathway F) before it evaporates may reduce the body cooling effect of that evaporation. In addition, in the lower permeability clothing, more cycles of adsorption-desorption of moisture can be expected on its way out of the clothing due to the higher microclimate vapor pressures that are observed (17, 21). For those cases where the apparent evaporative cooling efficiency is found to be higher than the η_{real} values in Fig. 8, however, other mechanisms must play a role apart from moisture evaporating out of the suit (i.e., pathways C and D).

Some authors recognized the importance of condensation in clothing for thermal comfort and heat loss (14) but attribute the effect of condensation on overall heat transfer to increased conduction of heat in the fabrics. However, others have shown that the increase in wet conduction of clothing materials (pathway C) is low. Chen et al. (6) observed increases in clothing heat conduction of 2–8%, when water starts to accumulate in the clothing layers, and Bröde et al. (4) of 9%, although these may still have included some evaporation-condensation heat transfer due to the methodology used. Richards (35) tested the change in clothing fabric conductivity in relation to moisture content and calculated that the changes in

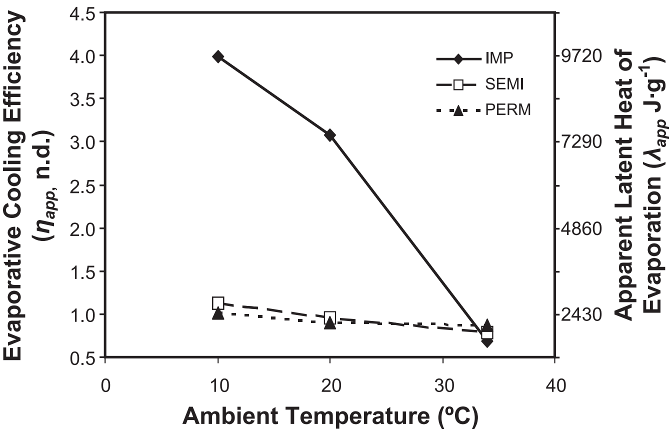

Fig. 7. Apparent evaporative cooling efficiency (η_{app}, from *Eq. 5*) and apparent latent heat of evaporation (λ_{app}, from *Eq. 7*) at different ambient temperatures. The measurements with different underwear for IMP, SEMI, and PERM outerwear are averaged.

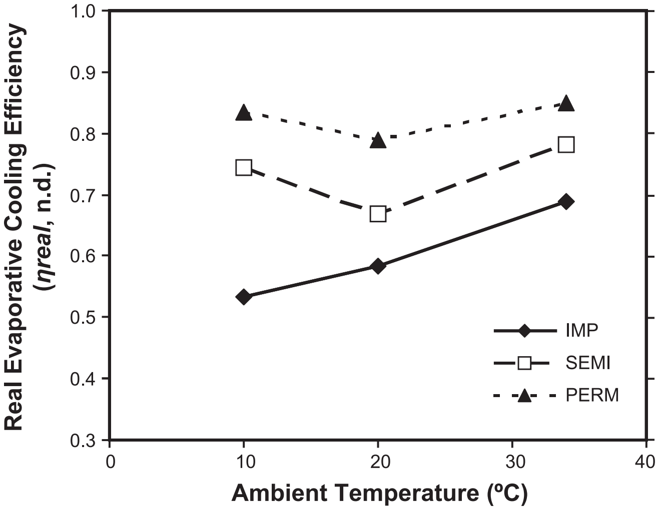

Fig. 8. Real evaporative cooling efficiency (η_{real}, from *Eq. 6*) based on the ratio of the calculated "real evaporative heat loss" [determined from wet heat loss at 34°C (E_{real}, from *Eq. 2*)] over the heat loss of the evaporation as determined from mass loss (E_{mass}, from *Eq. 3*).

conductivity of a clothing ensemble including air layers due to wet conduction would be $<3\%$. Thus the major component of the higher than expected heat transfer at lower temperatures must be attributed to the microclimate heat pipe effect alone (pathway D). This mechanism increases η_{app} in clothing with low permeability to ∼4, and thus λ_{app} up to more than four times the standard value.

The findings of the present study indicate that, if heat loss calculation in a study is purely based on mass loss, substantial errors can be caused. Absolute errors measured on the manikin for the conditions studied here for IMP, SEMI, and PERM were +5, +22, and + 19 W at 34°C, respectively, −37; +5, and +15 W, respectively, at 20°C; and −58, −11, and −1 W, respectively, at 10°C. This is equivalent to errors of +30% to −38% of total measured heat loss in the conditions used (static, 0.5 m/s). Despite the low amounts of water evaporated from the IMP suit via openings, the effect on total heat loss is dramatic (Fig. 6). Translated into heat storage in a human subject (70 kg), the largest error of 58 W is equivalent to a change of 0.86°C /h in mean body temperature. Also with such errors, data interpretation becomes difficult: e.g., Rossi et al. (37) observed that, for clothing incorporating a laminate, vapor resistance based on measurements of weight loss increases with reducing temperature. They also observed increasing amounts of condensation with reducing temperatures. If these data are then applied to assessing the wearer's heat load, and heat losses are calculated based on dry heat resistances and the observed vapor resistances, the heat released by the condensation is not taken into consideration, causing an underestimation of heat losses. Also for many manikins, measurement of vapor resistance is based on mass loss (2, 6). Assuming an evaporative cooling efficiency of unity ($\lambda = 2{,}430$ J/g) will introduce an error in their results, as demonstrated in the present experiment. Using either heat loss or mass loss to calculate clothing vapor resistance in different manikins may actually explain a major part of the differences observed in results of interlaboratory comparison studies (36).

The observations provide strong evidence that the latent heat of evaporation (pathway E only) while wearing clothing is less than generally assumed. Values for λ for evaporation of human sweat have been debated in the literature, considering the effects of temperature, humidity, and sweat osmolality, but suggested values ranging from 2,696 J/g (16) to 2,595 (32, 38) and 2,398 J/g (33) have finally converged to the latent heat of evaporation of pure water (39), only dependent on temperature giving a number of 2,430 J/g at 30°C (15). Wenger (39) showed that the higher values observed before (16, 32, 38) were due to erroneous assumptions or attributable to error margins present in the equipment and analysis method. Given these literature values, the use of distilled water instead of real sweat in the present study should not affect the conclusions.

It should be noted that all these studies apart from Hardy (16) used calorimetry of the human body. What this technique determines are the heat losses from the calorimeter's content, i.e., the person with their clothing and the surrounding air as one mass. Hence, this technique does not discriminate between heat for evaporation taken from the body, from the clothing, from the clothing microclimate, or from the air in the calorimeter. This total amount of heat taken by evaporation was found to be constant for a certain temperature (15, 39), but the present study clearly shows that the source for this heat of evaporation is not only the body but must also be the environment within the clothing.

This process of part of the heat coming from the environment and part from the skin was earlier described in relation to the heat of sorption and desorption in wool fibers when humidity is changed. David (7) observed that only 30–50% of this heat affected heat loss from the skin. Also, Craig and Moffit (8) and Burton (in Ref. 7) pointed in this direction, although their heat balance analysis contained several estimations rather than measurements.

Since this study shows that for clothed people heat loss by evaporation is not well represented by mass loss of the clothed person, one question is whether other measures can be used. Mass loss from the nude body cannot be used since that includes moisture wicked into the clothing: at 34°C, without condensation, the clothing (averaged over all underwear) still gained 170 g. Since condensation would lead to extra mass gain of the clothing, the question arises whether the heat pipe effect may be estimated from clothing mass gain. However, the predictive value of this relation was low ($r^2 < 0.15$), although when cotton underwear was excluded, this rose to 0.63. This is due to the much higher absorption in cotton underwear due to wicking (290 g at 34°C), which masks the condensation effect. Shown by the 63% explained variance, this is less the case in low-absorption underwear, like the polyester and polypropylene underwear used. Furthermore, as the temperature is lowered to freezing or below, condensation will get more and more pronounced, and the weight gain of the clothing may become a good indicator for the condensation effect (28).

Conclusions

The main finding of this study is that, when evaporative heat loss from a clothed person is determined from the clothed person's weight change, substantial errors may be made. These errors can lead to overestimations of evaporative heat loss, mainly in the heat, or large underestimations of evaporative heat loss in the cold. Absolute errors ranged from +22 to −58 W, which is equivalent to errors of +30% to −38% of total measured heat loss in the conditions used (static, 0.5 m/s).

The second and third main findings were the identification of the mechanisms behind this error. It was shown that, when wearing clothing, the latent heat of evaporation of moisture from the skin is not completely taken from the body, leading to an evaporative cooling efficiency that is <1 (η_{real} decreases from 0.8 to 0.55 when the permeability of the outer garment decreases). Also, when ambient temperature drops below skin temperature, this effect will be compensated for by a microclimate heat pipe effect, which transfers latent heat from skin to clothing (from where it is lost to the environment by increased radiation and convection) without losing moisture (weight) from the clothing. This pushes the apparent evaporative cooling efficiency, η_{app}, above the value of η_{real}, first toward unity, and at cooler temperatures and for low permeability clothing even substantially above unity. Not taking these effects into consideration can lead to substantial errors in the estimates of heat loss from a clothed person and may put workers at risk. The model developed here explains human subject data on evaporative heat loss that previously seemed to be contradictory.

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