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TNO-report

IZF 1989-32

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THE EFFECT OF MOISTURE ABSORPTION IN
CLOTHING ON THE HUMAN HEAT BALANCE

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Report No.: IZF 1989-32

Title: The effect of moisture absorption in clothing on the human heat balance

Authors: drs. W.A. Lotens and drs. G. Havenith

Institute: TNO Institute for Perception

Date: October 1989

No. in Program of Work: 736.1

SUMMARY

A theory of moisture absorption in clothing, with the associated effects of heat transfer, was developed based on the assumption that clothing can be regarded as a moisture buffering capacitor enclosed between heat and vapour resistances, and covered with the adjacent air layer.

The theory was checked with an experiment involving four subjects. They wore heavy woolen clothing, which was either initially dried or wetted, in both a warm and a cool environment. The experimental results confirmed satisfactorily the theoretical predictions that (1) the dry and evaporative heat loss will change in time and will both converge for the dry and moist garments to the equilibrium condition, (2) the clothing surface temperature and humidity are bound to a straight line on the psychrometric chart, (3) dry garments cause higher heat strain than wet garments, (4) the time course is predictable from the buffering capacity of the clothing and the heat transfer coefficient, and (5) the apparent heat and moisture transfer coefficients are bound to a linear relationship, revealing the true values only during equilibrium. Contrary to the expectation the observed vapour resistance is lower in the heat than in the cold, probably due to differences in sweat distribution.

Het effect van vochtabSORPTIE in kleding op de warmtebalans

W.A. Lotens en G. Havenith

SAMENVATTING

Een theorie over vochtabSORPTIE in kleding en de daarmee gepaard gaande dynamische warmtetransportverschijnselen werd uitgewerkt, uitgaande van de veronderstelling dat kleding beschreven kan worden als een buffercapaciteit tussen damp- en warmteweerstanden en bedekt met de aanhangende luchtlaag.

De theorie werd getoetst met een experiment waarin vier proefpersonen dikke wollen kleding droegen die van tevoren was gedroogd of juist bevochtigd. Dit werd gedaan zowel in een warm als in een koel klimaat. De resultaten bevestigen de theoretische voorspellingen dat (1) de droge en natte warmte-afgifte in de tijd veranderen en beide convergeren voor droge en vochtige kleding naar de evenwichtstoestand, (2) de temperatuur en absolute vochtigheid van het kledingoppervlak aan elkaar gekoppeld zijn en een rechte lijn geven op een psychrometrische kaart, (3) droge kleding een grotere warmtebelasting geeft dan natte kleding, (4) het tijdsverloop van het absorptieproces voorspeld kan worden uit de absorptiecapaciteit en de warmte-overdrachtscoëfficiënt van de kleding, en (5) de schijnbare warmte- en dampoverdrachtscoëfficiënten een lineair verband vertonen en slechts in de evenwichtsconditie hun echte waarde aannemen. In tegenstelling tot de verwachting is de gemeten dampweerstand in de warmte lager dan in de koele omgeving wat waarschijnlijk toe te schrijven is aan verschillen in verdeling van het zweet.

1 INTRODUCTION

The absorption property of fabrics is generally regarded as a prime factor in comfort. There is no clear insight, however, in the contribution to comfort of the many mechanisms involved, including fibre rigidity, wicking, clinging, liquid buffering, drying, and thermal effects. Some of these mechanisms are relevant only during transient conditions. In particular the thermal effects are interesting in this respect, since clothing heat transfer is usually studied in equilibrium conditions, whereas in reality wearers are almost constantly in transient conditions.

Absorption is the link between dry and wet heat transfer in transient conditions. When absorption takes place, the heat of sorption is liberated and consequently the dry heat flow increases, whereas the wet heat flow is decreased. During desorption the opposite occurs. Thus the clothing as worn is continuously buffering and dissipating moisture, with associated heat effects. The quantitative description of this process is the subject of this study.

The importance of the absorption capacity of clothing for actual wear has long been recognized, but hardly been quantified. At the level of fibres the absorption theory had been developed by Cassie and Baxter (1940) and Henry (1939), explaining in particular the surprisingly long time constants involved. Woodcock (1962) recognized the implications for fabrics, but focussed on the vapour resistance. Spencer-Smith (1976, 1978) developed part of the theory involved, but restricted himself to physical measurements, and so did Farnworth (1986), applying a more sophisticated mathematical model.

David (1965) was the first to report the effects of absorption in clothing, using a thermal manikin. He too found longlasting effects.

Recently, De Dear et al. (1989) reported a manikin/subjects study on the thermal effects of moving from one environmental humidity to another with absorbing and non-absorbing clothing. They described part of the effects by a regression model.

The current study is aiming at a simple but realistic theory, predicting quantitatively the thermal effects of absorption on the heat balance of humans.

2 ABSORPTION THEORY

Clothing will be considered as a single layer of uniform properties, covered with the adjacent air layer. The relevant clothing properties

are the heat transfer coefficient, the vapour resistance and the moisture absorption capacity. The latter will be considered to be located in the middle of the clothing layer. Fig. 1 shows this in an electrical network, although the actual analogy to electrical phenomena is poor.

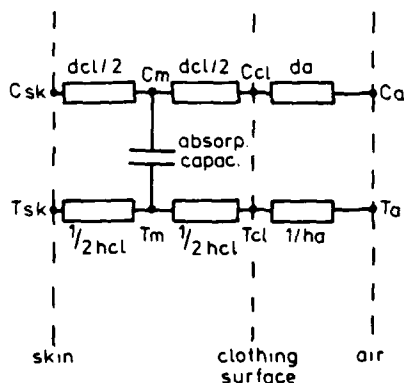


Fig. 1 The considered clothing system in an electrical analogon. The upper chain of resistances (vapour resistance d) and the lower chain of heat resistances ($1/h$) are connected by the water vapour absorption capacity of the clothing, located in the middle of the clothing layer.

For the description of the theory two locations in the clothing system are relevant. The first is the location of the absorption capacity and the second the interface between clothing and air. The latter place is most apt to experimental check of the theory, whereas the former is decisive for the speed of transient phenomena.

Clothing material has the heat storage capability:

$$\text{Storage} = W C_p \frac{dT_m}{dt} \quad (\text{W/m}^2) \quad (1)$$

where W = fabric weight (g/m^2)

C_p = specific heat ($\text{J/g}^\circ\text{C}$)

T_m = temperature in the middle of the clothing ($^\circ\text{C}$).

The magnitude of the heat storage is usually small compared to the amounts of heat that flow from the skin. Only during fast transients,

like step changes in temperature or radiation, the effect is appreciable, but only so for a short time. During a step change of 10°C , heavy clothing ($h_{cl} = 4 \text{ W/m}^2\text{C}$, 500 g/m^2) will store initially 40 W/m^2 , which dies away with a time constant of 120 s, while light clothing ($h_{cl} = 16 \text{ W/m}^2\text{C}$, 200 g/m^2) stores initially 160 W/m^2 , dying with a time constant of 12 s. Thus for heavy clothing the heat storage has decreased to below 10 W/m^2 within 3 min and for light clothing within 35 s. A flow of 10 W/m^2 is small compared to the heat production of humans (50 W/m^2 in rest, increasing to a multiple during work) and for the sake of simpleness the heat storage will be neglected in this study.

The moisture storage capability depends on the sorption capacity of the fibres, which is characterized by the standard regain (Reg), the amount of water absorbed at 65% relative humidity (rh) in 100 g of dry fibre. For all fibres the absorbed water (Ma) is approximately in the same way dependent on the relative humidity (rh), following a typical absorption function f . Thus fabrics of various fibre types differ only in the proportionality factor Reg:

$$Ma = \frac{\text{Reg}}{100} f(\text{rh}) \text{ (g H}_2\text{O/g fibre)} \quad (2)$$

and a change in Ma is defined by

$$dMa = \frac{\text{Reg}}{100} f' \text{ drh (g/g)} \quad (3)$$

where f' = derivative of f with respect to rh.

This change in moisture content of the fibre is associated with the liberation or absorption of the differential heat of sorption Q_v , which is also a typical function of the relative humidity. The heat involved is thus:

$$\text{Abs} = W Q_v \frac{dMa}{dt} = \frac{W Q_v \text{Reg}}{100} f' \frac{d \text{rh}}{dt} \text{ (W/m}^2\text{)} \quad (4)$$

where W = weight of fabric (g/m^2).

Abs is the power involved in the transition from an evaporative into a dry heat flow (during absorption) or the other way around (during desorption). The sum of dry and evaporative heat flows is for any place in the ensemble not affected by this transition:

$$\text{Dry} + \text{Evap} = \text{Constant}$$

Since it was assumed that the heat storage in the clothing can be neglected, the total heat flow from the skin to the clothing must equal the flow from the clothing to the environment:

$$\text{Dry}_{sc} + \text{Evap}_{sc} = \text{Dry}_{ca} + \text{Evap}_{ca} \quad (5)$$

where sc refers to skin $\rightarrow$ clothing
ca refers to clothing $\rightarrow$ air.

Similar equations hold for any place inside the clothing system. With reference to the clothing surface the four terms in equation 5 are defined by:

$$\text{Dry}_{sc} = h_{cl} (T_{sk} - T_{cl}) \quad (6)$$

$$\text{Evap}_{sc} = Q_v \frac{D}{d_{cl}} (C_{sk} - C_{cl}) \quad (7)$$

$$\text{Dry}_{ca} = h_a (T_{cl} - T_a) \quad (6a)$$

$$\text{Evap}_{ca} = Q_v \frac{D}{d_a} (C_{cl} - C_a) \quad (7a)$$

where h = heat transfer coefficient ($W/m^2^\circ C$)
 D = diffusion coefficient (m^2/s)
 d = diffusion air equivalent (m)
 T = temperature ($^\circ C$)
 C = water vapour concentration (g/m^3)
 sk refers to skin, cl to clothing, and a to air.

Substitution of 6, 6a, 7 and 7a into 5 reveals:

$$\begin{aligned} T_{cl}(h_a + h_{cl}) + C_{cl} Q_v D \left(\frac{1}{d_a} + \frac{1}{d_{cl}} \right) = \\ = h_{cl} T_{sk} + h_a T_a + Q_v D \left(\frac{C_{sk}}{d_{cl}} + \frac{C_a}{d_a} \right) \end{aligned} \quad (8)$$

Equation 8 represents a linear relationship between T_{cl} and C_{cl} for any set of skin and environmental conditions. In Fig. 2 the relationship is plotted in a psychrometric chart.

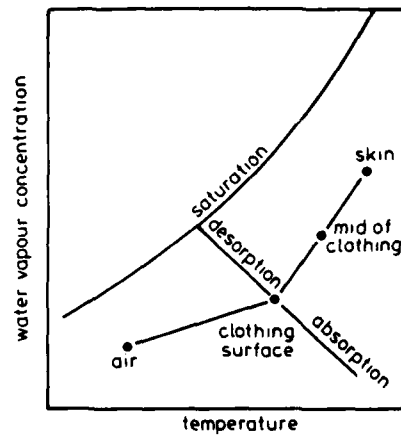


Fig. 2 Psychrometric chart, showing the condition at the skin and in the air. The straight line is the locus of solutions of equation 8 for the temperature and vapour concentration at the clothing surface. The condition of the mid of the clothing is always halfway the skin and the surface condition.

Any point at the line represents a solution for equation 8. The difference between the solutions is the rate of absorption or desorption. During absorption the clothing is relatively dry, C_{cl} is low and due to liberation of heat of sorption T_{cl} is high. This is the case in the bottom part of the line. During desorption C_{cl} is high and T_{cl} is low, a condition represented by the top part of the line. In between these two, there is a point of equilibrium, for which holds:

$$Dry_{sc} = Dry_{ca}$$

$$Evap_{sc} = Evap_{ca}$$

The condition of the clothing thus tends to converge to the equilibrium point, starting from the extremities. So far the theory is essentially the same as presented by Spencer-Smith (1978).

The speed of convergence depends on the sorption process, which is defined by:

$$Abs = Evap_{sc} - Evap_{ca} \quad (9)$$

As was anticipated, for the calculation of transients Evap_{sc} and Evap_{ca} should be defined with reference to the midpoint of the clothing, rather than to the surface:

$$\text{Evap}_{sc} = 2 Q_v \frac{D}{d_{cl}} (C_{sk} - C_m) \quad (7b)$$

$$\text{Evap}_{ca} = 2 Q_v \frac{D}{d_{cl} + 2 d_a} (C_m - C_a) \quad (7c)$$

Similarly Dry_{sc} and Dry_{ca} read:

$$\text{Dry}_{sc} = 2 h_{cl} (T_{sk} - T_m) \quad (6b)$$

$$\text{Dry}_{ca} = \frac{2 h_a h_{cl}}{2 h_{cl} + h_a} (T_m - T_a) \quad (6c)$$

Similar to equation 8 a relationship between C_m and T_m can be found:

$$\begin{aligned} T_m \left(\frac{2 h_a h_{cl}}{2 h_{cl} + h_a} + 2 h_{cl} \right) + C_m Q_v D \left(\frac{2}{d_{cl}} + \frac{2}{d_{cl} + 2 d_a} \right) = \\ = 2 h_{cl} T_{sk} + \frac{2 h_a h_{cl}}{2 h_{cl} + h_a} T_a + Q_v D \left(\frac{2 C_{sk}}{d_{cl}} + \frac{2 C_a}{d_{cl} + 2 d_a} \right) \end{aligned} \quad (8a)$$

When the midpoint of the clothing changes in relative humidity by $d rh$, equation 4 can be written as:

$$\begin{aligned} \text{Abs} = \frac{W Q_v \text{Reg } f'}{100} \frac{dC_m / C_{sat}}{dt} = \\ = \frac{W Q_v \text{Reg } f'}{100 \cdot C_{sat}} \left(\frac{dC_m}{dt} - \frac{C_m}{C_{sat}} C' \frac{dT_m}{dt} \right) \end{aligned} \quad (4a)$$

where C_{sat} = saturation concentration at temperature T_m (g/m^3)
 $C' = dC_{sat}/dT_m$ ($\text{g/m}^3 \cdot ^\circ\text{C}$).

From equation 8a it follows that (at stationary boundary conditions):

$$\frac{dT_m}{dt} = - \frac{Q_v D \left(\frac{2}{d_{cl}} + \frac{2}{d_{cl} + 2 d_a} \right) \frac{dC_m}{dt}}{\frac{2 h_a h_{cl}}{2 h_{cl} + h_a} + 2 h_{cl}} \quad (10)$$

When equations 7b and 7c are substituted in 9, and 9 and 10 are substituted in equation 4a, a non-linear differential equation is obtained:

$$\frac{dC_m}{dt} = \frac{C_m - C_e}{\frac{W \text{ Reg } f'}{100.4 \cdot C_{\text{sat}}} \left(\frac{dcl (dcl + 2 da)}{D (dcl + da)} + \frac{C_m}{C_{\text{sat}}} C' \frac{Q_v}{hcl} \frac{(2 hcl + ha)}{(hcl + ha)} \right)} \quad (s) \quad (11)$$

where C_e = equilibrium value for C_m .

Equation 11 can be considered as a linear first-order differential equation with a continually changing time constant equal to the denominator of 11. This time constant is long for: large absorption capacity ($W \text{ Reg}$), high relative humidity (f' and C_m/C_{sat}), low temperature (low C_{sat}), thick clothing (high dcl and low hcl), and still air (low ha and high da). The change of the time constant during the process is not so large, becoming shorter during desorption and longer during absorption.

For a .6 clo cotton garment of 300 g/m^2 , equation 12 predicts during comfortable conditions a time constant of about 2 minutes, when equilibrium is near. This is only an approximate value, since in reality the surface of the clothing has a shorter time constant than the innermost layers. In order to keep the theory simple such a distinction in time constants will not be made in this study.

A quantitative predictive model should allow the calculation of the transient effects. Such a model has been implemented on a computer (Program MDC, Moisture Dynamics of Clothing) to obtain numerical results. For the clothing specified in Table I, the results are given in Fig. 3.

Table I Specification of the clothing and boundary conditions in the calculation of Fig. 3.

Garment	Skin	Environment
hcl = $8 \text{ W/m}^2\text{°C}$	Tsk = 35°C	Ta = 15°C
dcl = 11 mm	Csk = 25 g/m^3	Ca = 8 g/m^3
W.Reg/100 = 50 g/m^2		da = 4 mm
		ha = $12 \text{ W/m}^2\text{°C}$

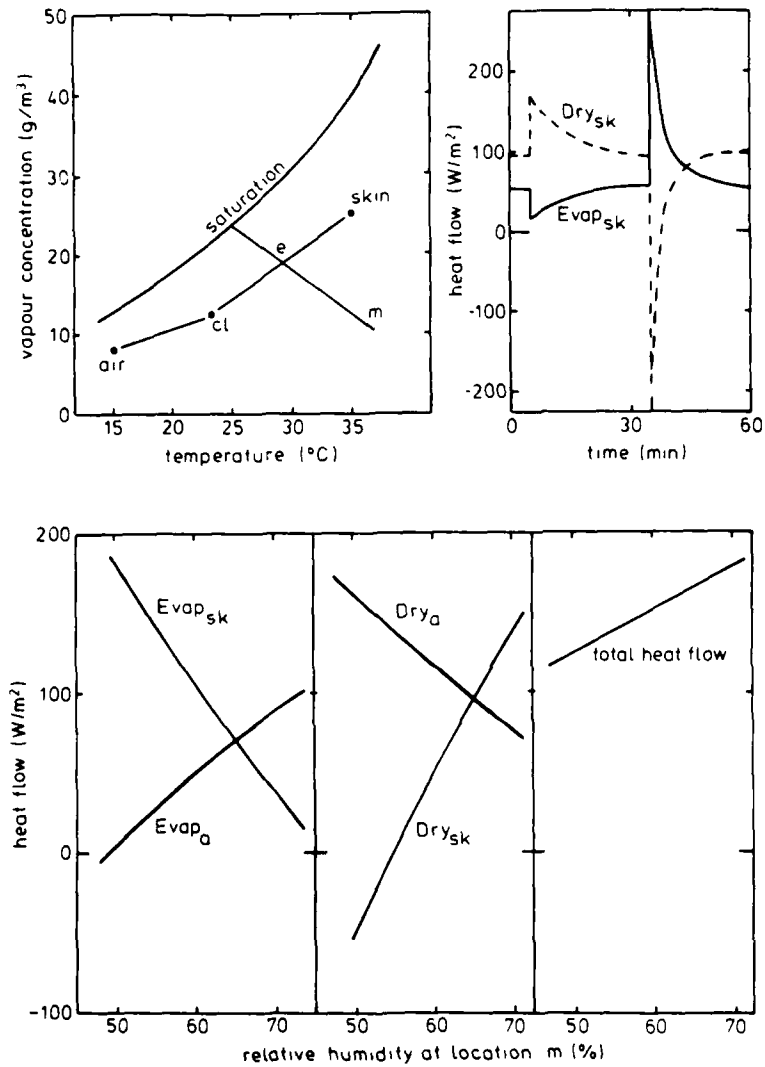


Fig. 3 Results of a numerical analysis of transients in the clothing specified in Table I. Top left panel: psychrometric chart with the locus of solutions for the middle of the clothing (m). Top right panel: skin heat flow components following wetting of the clothing (min 5) and drying (min 35). Bottom panel: heat flows at the skin and to the air, and total heat flow as a function of clothing relative humidity.

The top-left panel shows the skin, air and clothing surface conditions in a psychrometric chart. The line is the locus of solutions of equation 8. In the top-right panel, the responses are shown of the dry and evaporative heat flow to full saturation of the clothing (100% rh, min 5) and fully drying the clothing (0% rh, min 40). In particular for dry clothing the rate of absorption is so high that the clothing temperature increases to over 35°C, resulting in a negative dry heat flow between skin and clothing. For the parameters chosen, the response time is of the order of 8 min. The bottom panel of Fig. 3 shows the resultant heat flows to and from the clothing as a function of the relative humidity of the clothing. At 65% there would be equilibrium. Depending on the relative humidity, the various heat flows may change dramatically and in particular the differences between the heat flows to and from the clothing may be large. In the same graph, finally, the total heat flow is shown that leaves the skin. This flow increases with the relative humidity of the clothing, indicating that moist clothing is less stressful than dry clothing.

The heat flows in Fig. 3 at the skin and into the air are not the same as those of equations 7b and 7c. In those equations the clothing condition as to Ccl is defined on the basis of Qv, the heat of sorption. At the skin there is liquid that evaporates and there the heat of evaporation He is pertinent. The evaporative heat flows from the skin and into the environment thus read:

$$\text{Evap}_{sk} = \frac{2 \text{ He } D}{dcl} (C_{sk} - C_m) \quad (7d)$$

$$\text{Evap}_a = \frac{2 \text{ He } D}{dcl + 2 da} (C_m - C_a) \quad (7e)$$

where the subscripts sk and a refer to skin and air, and should be distinguished from the earlier introduced subscripts sc and ca, which referred to the heat balance in the clothing. For reasons of symmetry also Dry_a and Dry_{sk} are introduced, but these equal Dry_{ca} and Dry_{sc}, respectively.

In experiments only the heat loss of subject plus clothing is really accessible for measurement. This is Dry_a + Evap_a. These equal Dry_{sc} + Evap_{sc}, defined by 6b and 7d:

$$\text{Dry}_a + \text{Evap}_a = 2 hcl (T_{sk} - T_m) + \frac{2 \text{ He } D}{dcl} (C_{sk} - C_m) \quad (12)$$

Since T_m and C_m are not readily available this equation must be converted to terms in T_{cl} and C_{cl}, recognizing that:

$$T_m = T_{cl} + \frac{Dry_a}{2 hcl} \quad (13)$$

$$C_m = C_{cl} + \frac{dcl \text{ Evap}_a}{2 He D} \quad (14)$$

Substitution of 13 and 14 in 12 reveals that

$$Dry_a + Evap_a = hcl (T_{sk} - T_{cl}) + \frac{He D}{dcl} (C_{sk} - C_{cl}) \quad (12a)$$

In this equation all variables except hcl and dcl are measurable and equation 12a is thus one equation with two unknown variables. The solutions are multiple and form a straight line when hcl is plotted against $1/dcl$. Only during real equilibrium the actual clothing parameters are found:

$$hcl = \frac{Dry_a}{T_{sk} - T_{cl}} \quad (15)$$

$$dcl = \frac{He D (C_{sk} - C_{cl})}{Evap_a} \quad (16)$$

When equations 15 and 16 are applied before equilibrium is settled, the apparent clothing parameters are obtained.

The sorption theory thus leads to a number of important notices that are suited for experimental verification:

- I dry and moist garments show rather different Dry_a (and $Evap_a$), converging to the same equilibrium value;
- II the same is true for T_{cl} and C_{cl} , which are bound to the straight line in Fig. 2;
- III the body heat loss is lower for a dry than for a moist garment, resulting in a higher heat strain;
- IV the time course is predicted by equation 11;
- V when applying a heat balance technique to obtain hcl and dcl , the apparent values change with the time and the real values are obtained only when equilibrium is reached. The apparent hcl and $1/dcl$ lay on a straight line.

3 EXPERIMENTAL VERIFICATION

3.1 Methods

The theory was tested in an experiment where subjects performed work on a bicycle ergometer, clothed in absorbing clothing. The outer garment was either initially dried or wetted to approximately 90% rh. According to equation 12a, the apparent values of h_{cl} and $1/d_{cl}$ found during the absorption or desorption phase should lay on a straight line, and the equilibrium, that is not likely to be reached within an acceptable experimental trial, is somewhere in between. To find the equilibrium point, a second line, crossing the first, would be helpful. This can be obtained by repeating the measurements in other environmental conditions, as equation 13a again predicts. In the experiment a cool (9.5°C, 52% rh) and a warm (26.8°C, 24% rh) condition were chosen, with predominantly dry and evaporative heat transfer, respectively. For these four conditions (moist/dry combined with warm/cool) the heat balance equation was determined at three consecutive times to show the process of convergence of the moist and dry conditions with time.

Details about the experimental set-up are given below.

- Clothing. Cotton fatigues (1300 g) under a woolen fire-fighters garment (1700 g for the jacket and 900 g for the trousers). The fabric's outer surface area is 2.2 m². Completed with rubber boots, rubber gloves, respirator and impermeable hood, together .5 m² area.
- Clothing wetness. Dry fatigues and either tumbler-dried woolen garment, or tumbler-dried and then wetted with 400 g water in the jacket and 300 g in the trousers, giving relative humidities of around 10 and 90%, respectively.
- Subjects. 5 males in the age of 21 to 25 years, with a DuBois surface area between 1.7 and 2.1 m² (average 1.9 of which 1.6 m² is covered with clothing and .3 m² with impermeables), training level varying from bad to very good. One subject completed only 2 conditions due to illness.
- Environment. Either 26.8°C, 24% or 9.5°C, 52%, resulting water vapour concentrations of 6 and 4.8 g/m³, respectively. Horizontal, slightly turbulent air flow of average speed .25 m/s.
- Work. Bicycle ergometer work of 70 W external work (W_{ext}), resulting in 442 W metabolic work (M) on the average. Due to a malfunction of the bicycle feedback control system and individual variation the metabolic energy production has not been the same for all conditions, but varied from 380 to 480 W.

- Sessions. Duration 1 hour. Heat balance has been determined at min 30, 45 and 60. Preparation of the subjects took place in a room at 23°C. The subjects entered the climatic chamber immediately upon donning the conditioned woolen garment.
- Measurements. O₂ uptake, CO₂ production, heart rate, rectal temperature, skin temperature at seven sites (head, chest, back, upper arm, lower arm, thigh, calf), skin vapour concentration at the same sites, clothing surface temperature at the same sites, continuous weight registration, perceived temperature and wetness, weight of garments before and after test.
- Data reduction. Heat balance data (Evap_a and heat storage, Sto), were transformed to M = 442 W by means of regression analysis (r = .95 for Evap, .8 for Sto). Respiratory heat loss and dry heat loss from impermeable parts are calculated by:

$$\text{Resp} = .0024 M (42 - T_a) + .0014 M (34 - T_a)$$

$$\text{Dry}' = 1.93 \Delta T$$

where 1.93 = heat conduction from head, hands and feet, calculated from the insulation thickness and the area (W/°C)

ΔT = temperature difference between the average of head, lower arms and calves, and air.

3.2 Results

Prediction I (wet and dry conditions show converging heat balance)

The heat balance has the form

$$M = W_{\text{ext}} + \text{Resp} + \text{Dry}' + \text{Dry}_a + \text{Evap}_a + \text{Sto}$$

where Dry' is the heat loss of head, hands and feet. The heat balance amounts then in the cold to

$$442 = 70 + 57 + 46 + \text{Dry}_a + \text{Evap}_a + \text{Sto}$$

and in the heat to

$$442 = 70 + 46 + 13 + \text{Dry}_a + \text{Evap}_a + \text{Sto}$$

The average values of Dry_a , $Evap_a$ and Sto are shown in Fig. 4. In concert with prediction I of the theory there is convergence in time of the wet and dry conditions.

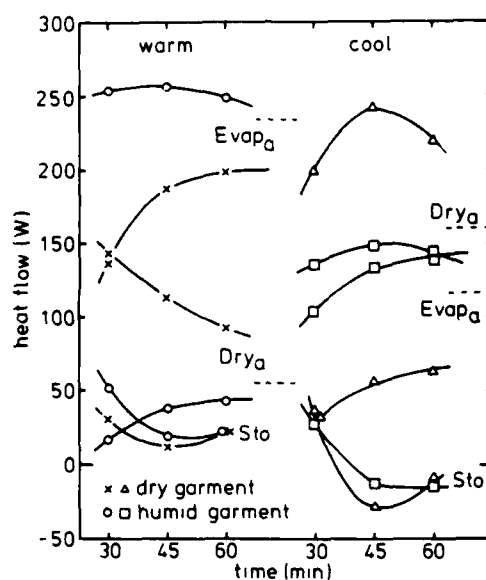


Fig. 4 Experimentally determined heat flows as a function of time for the cool and the warm environment, both starting with a dry and a humid garment.

The difference in environmental condition between the preparation room and the climatic chamber causes a strong initial transient, enhanced by the transient in skin condition (Fig. 8) associated with the onset of work. After about 30 min these boundary conditions become more stable and from that time on $Evap_a$, Dry_a and Sto show the expected behaviour. Although the equilibrium comes nearer in the second half hour, it is by far not reached at min 60.

Prediction II (T_{cl} and C_{cl} are on a straight line)

That after 60 min there is still no equilibrium, is confirmed by the surface temperatures of the clothing, shown in Fig. 5.

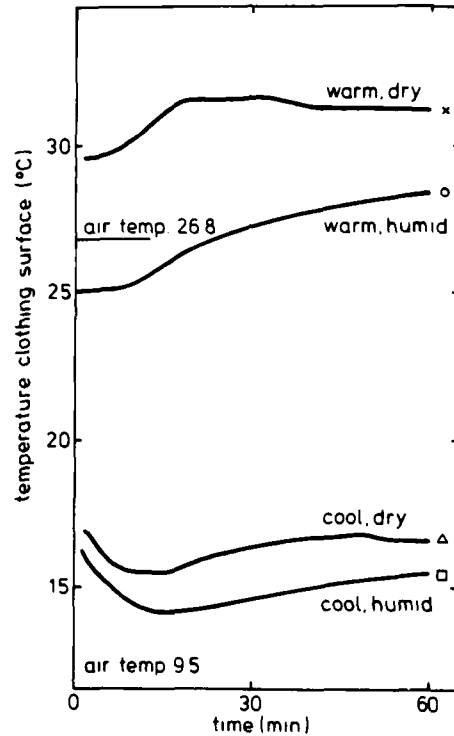


Fig. 5 Clothing surface temperature as a function of time for the cool and the warm environment, both with a dry and a humid garment.

The dry conditions both show higher temperatures than the corresponding humid conditions, due to the liberation of heat in the dry condition and the absorption in the humid case. The curves are pairwise slowly converging as predicted. The difference between T_{cl} and T_a is largest in the cool, dry condition and smallest in the warm, humid condition. In Fig. 6 these gradients are plotted against Dry_a for the four conditions and for min 30, 45 and 60.

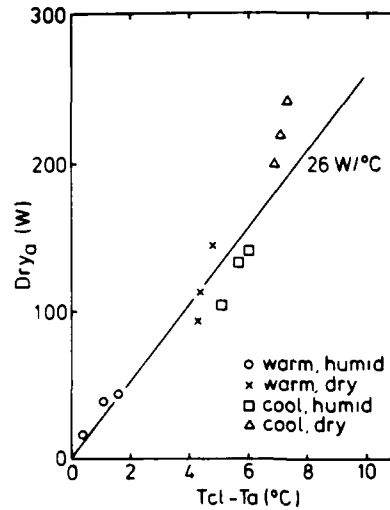


Fig. 6 Correlation between the dry heat flow to the air and the temperature gradient between garment surface and air. The three data points for each condition pertain to the minutes 30, 45 and 60.

There is a proportionality, revealing a heat transfer coefficient of 26 W/°C, which corresponds to 11.8 W/m²°C. With a radiative heat transfer coefficient of 4.5 (assuming an emission coefficient of 1 and an effective radiating surface area of 90% of the clothing area), this leaves for the convective part of h_a (h_c) a value of 7.3. The values of C_{cl} may now be calculated according to

$$C_{cl} = C_a + \frac{\text{Evap}_a}{A_{cl}} \frac{da}{He \cdot D} = C_a + \frac{\text{Evap}_a}{A_{cl} h_c L} \quad (\text{g/m}^3) \quad (17)$$

where A_{cl} = the clothing surface area (2.2 m²)
 L = Lewis constant (2.34 °Cm³/g).

The values of C_{cl} thus found are plotted against T_{cl} in Fig. 7 and also the predicted values are indicated, applying equation 8.

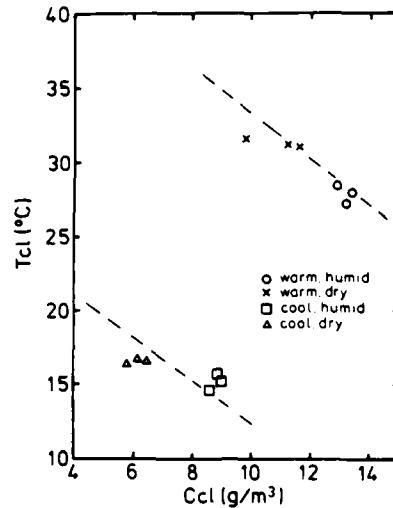


Fig. 7 The data points and the predicted relationship between the clothing surface temperature and vapour concentration in their approach to equilibrium. The three data points per condition pertain to minutes 30, 45 and 60.

For the calculation of the theoretical lines the actual T_{sk} and C_{sk} are used, as well as the resultant h_{cl} and d_{cl} which will be dealt with later. The fact that the data points in Fig. 7 are not exactly on a straight line is largely due to non-stationarity of the skin temperature and vapour concentration.

Prediction III (dry clothing produces higher heat strain)

The effect of environmental temperature and clothing humidity is reflected in the skin temperature and vapour concentration. Fig. 8a shows that the skin temperature is higher for dry than for humid clothing and the same holds for the vapour concentration, except for the cool condition at min 60. The difference in vapour concentration is not large enough, however, to become statistically significant.

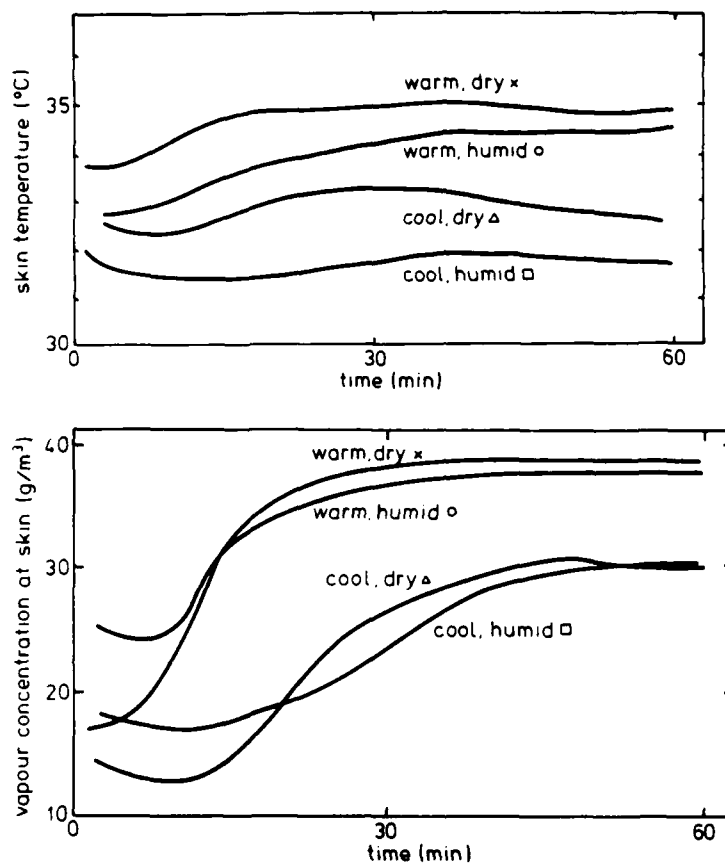


Fig. 8 Skin temperature (a) and skin vapour concentration (b) as a function of time.

There are more indications of higher heat strain in dry clothing, which are collected in Table II. Of the included variables only T_{sk} and sweat production are statistically significantly different between dry and humid clothing, but all variables indicate the same trend. During transient condition skin temperature is higher in dry clothing, rectal temperature is marginally higher, heart rate is higher (probably due to skin temperature), the skin relative humidity is slightly lower, and the sweat production is considerably higher.

Table II Indicators of heat strain at min 60. Tsk is skin temperature, Tr is rectal temperature, HR is heart rate, RHsk is skin relative humidity, SP is sweat production.

Condition	Tsk (°C)	Tr (°C)	HR (min ⁻¹)	RHsk (%)	SP (g/h)	heat rating	wetness rating
warm, dry	34.9	37.8	129	98	506	very warm	wet everywhere
warm, humid	34.5	37.7	124	98	161	warm	wet everywhere
cool, dry	32.6	37.7	114	86	206	slightly warm	locally wet
cool, humid	31.6	37.6	111	90	30	slightly warm	locally wet

The subjective heat and wetness ratings are different between the warm conditions only. It should be noted that the number of subjects is too low to expect any significant difference in subjective ratings.

Prediction IV (time course predicted by equation 11)

The final values of Tsk and Csk, and the estimated real values of hcl and dcl have been used to predict the time course of Dry_s by means of the computer program MDC. This is thus a simulation with constant boundary conditions, in contrast to the experiment in which during the first halfhour (warm environment) or three quarters of an hour (cool envir.) the skin condition was changing. In Fig. 9 the result of the simulation is shown together with the measured values for Dry_s.

In the warm conditions the prediction is close to the measurement, but in the cool condition there is some deviation due to the continuing change in skin humidity until min 45. Both in the warm and in the cool conditions the predicted convergence seems somewhat slower than the measured convergence. It is hard to estimate the actual time constants from the half hour period available, but the time constant for convergence is of the order of 30 min in the warm and 50 min in the cool condition.

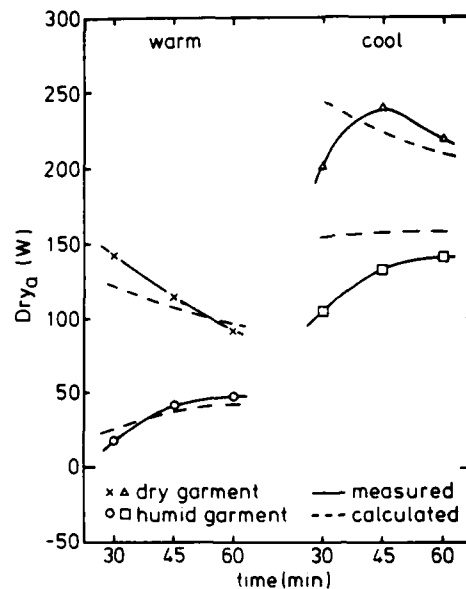


Fig. 9 The measured (solid lines, same as Fig. 4) and the predicted (interrupted lines) dry heat loss to the environment as a function of time.

Also the moisture content of the clothing and the sweat evaporation after min 60 contains some information on the time course, but this information is an integration over the full experimental session and is not simple to deduct theoretically, due to the dry conditioning of the fatigues in all sessions and the changes in skin condition in the first period of the session. Table III shows the moisture cumulation data.

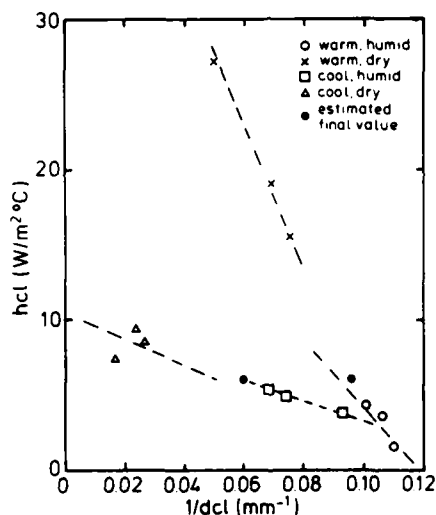
Table III Moisture cumulation over 60 min (in g).

Condition	Sweat prod.	Fatigues	Outer garment	Evaporated
warm, humid	161	175	-352	338
warm, dry	506	198	115	193
cool, humid	30	60	-225	195
cool, dry	206	35	112	59

The difference in moisture content of the outer garment between the humid and the dry condition is 233 g in the warm and 363 g in the cool condition. This is a qualitative support for the predicted shorter time constants in warm conditions according to equation 12. This is no more than an indication since it will be shown in the next section that dcl , which also has effect on the time constants, is not equal for the warm and the cool conditions.

Prediction V (hcl and $1/dcl$ are on a straight line)

When equations 16 and 17 are applied to the non-equilibrium situation, the apparent values of hcl and dcl are found. Only during equilibrium these equal the real values. Equation 13a predicts that there is a linear relationship between the apparent values of hcl and $1/dcl$. The predicted relationships have been calculated for the four conditions. Fig. 10 shows that in the heat there is good agreement with the prediction and in the cold also, with the exception of one point in the cool, dry condition.



The actual crossing is definitely outside the area where equilibrium is expected. Probable equilibrium values are estimated from extrapolations of $Evap_a$, Dry_a , $Tsk-Tcl$ and $Csk-Ccl$ and amount to $hcl = 6.0 \text{ W/m}^2\text{C}$ for both the warm and cool condition, and $dcl = 16 \text{ mm}$ in the cool condition, in contrast to 10.4 mm in the warm condition. The consistency of all data suggests that this is a true effect. One cause could be that the fatigues were much wetter in the warm conditions (water uptake $\approx 185 \text{ g}$) than in the dry conditions ($\approx 50 \text{ g}$), enabling liquid transport in addition to vapour transport, and another cause could be that in the heat the sweat production is for a larger proportion taking place at the legs, where the vapour resistance is lower than on the trunk, due to less insulation and more motion.

3.3 Discussion

The estimated final values for hcl ($6 \text{ W/m}^2\text{C}$ both in the heat and in the cold) and dcl (10.4 mm in the heat and 16 mm in the cold) are credible values for the type of clothing used. According to Lotens and Havenith (19..) cycling will decrease the insulation by some 25% for the cycling frequency used (50 rpm) and thus the estimated hcl for standing persons would be about 4.5. This is the heat transfer coefficient for a body that is half covered with 3 layers and for the other half with 2 layers of clothing. The local heat transfer coefficients would be

	standing			cycling	
	hcl	radiative part	convective part	hcl	convective part
3 layers	3.6	5/3	1.9	4.8	3.1
2 layers	5.4	5/2	2.9	7.2	4.7

The radiative part of hcl has been estimated here as

$$hcl_r = \frac{5}{\# \text{ intermittent layers} + 1} = \frac{5}{\text{total \# layers}} \quad (18)$$

as simple physics predict (Lotens, 1989).

Since the vapour resistance can be estimated as

$$d = 1.3 \frac{\lambda_a}{hclc} + .001 * \# \text{ layers (m)} \quad (19)$$

where λ_a = heat conductivity of air (.026 W/m²°C)
 $hclc$ = convective part of hcl

(Lotens and Havenith, 19..), the corresponding vapour resistances would be

	dcl (standing)	dcl (cycling)
3 layers	21 mm	14 mm
2 layers	14 mm	9 mm

The values thus found seem to agree reasonably well with the experiment. When it is mainly the trunk that sweats, the 3-layer (standing) condition is the most relevant (since the upper body moves not so much during cycling) whereas additional sweating on the moving legs may decrease the dcl value to somewhere in between 21 and 9 mm. The hypothesis that the difference in dcl between the warm and the cool condition is due to a shift in sweat distribution thus seems to be supported.

Another aspect of the sweat mechanism is the large difference in sweat production between the humid and dry condition. Table III showed that the sweat production was 345 g/h larger with a dry garment in the heat and 176 g/h in the cold. The concomitant differences in Tsk (1°C in the cold, .4°C in the heat) and in Tr (.1°C both in the cold and the heat) are insufficient to explain the difference in sweat production. According to Nadel et al. (1971) sweat production is largely controlled by core, mean skin and local temperature, and to a smaller magnitude by the rate of change in Tsk. These factors would explain only 45 g/h in the heat and 70 g/h in the cold in the current situation. Apparently the vapour concentration gradient has an enhancing effect on the sweat production. Although this has been reported earlier (Nadel and Stolwijk, 1973) the magnitude seems larger in this study. A cause could be the inhibitory effect of saturated skin on sweat production, known as hydromeiosis (Brown and Sargent, 1965).

The predictive formula for the time course (equation 1) looks rather complicated but some of the terms involved are more or less constant for not too extreme circumstances. Using the relationships 18 and 19 to convert dcl into hcl, the time constant in 11 can be simplified to

$$r = \frac{W \text{ Reg}}{100} \cdot \frac{60}{hcl} \text{ (s)} \quad (12a)$$

This is an approximate value, where $W_{Reg}/100$ is the absorption capacity (defined as g H₂O absorbed at 65% rh per m² of fabric).

For the garment in this experiment τ is $309 \times 60/6 = 3090 \text{ s} \approx 52 \text{ min}$. The transient will typically last for 3τ . This means that for the current highly absorbing clothing an experimental session should have lasted for about 3 h to arrive at the final values for hcl and dcl. With more usual clothing ($h = 8$, absorption capacity 50 g/m²) the τ time would be over 6 min and consequently the transient is extinguished about 20 min after the skin condition has stabilized. Such a time course was indeed measured by David (1965) when moving a clothed manikin from a dry into a humid environment. Determining the heat balance at an earlier moment than after 3τ with the intention to establish hcl and dcl would reveal wrong values.

De Dear et al. (1989) found for a 1 clo woolen ensemble of 96 g/m² absorption capacity a time constant shifting from 17 to 83 min while measuring heat loss with a manikin. The above rough estimate (12a) would amount to 15 min. Running the program MDC for their data provides time constants decreasing from 40 to 12 min when moving to the dry environment, and increasing from 10 to 20 min when moving to the humid environment. The apparent discrepancy with the manikin data might well be due to the earlier mentioned larger time constants for the inner clothing layers.

Although the model predicts heat flows and is not designed for comfort evaluation, some qualitative statements on comfort can be justified. It was predicted and confirmed that in the absorbing phase the total heat flow is lower than in the desorbing phase and the heat stress consequently larger. When approaching the equilibrium the difference becomes small. What would be the immediate effect of a change in conditions on the evaporative and the dry part of the heat flow separately? According to the theory the sum of the two is constant for small excursions and they are consequently complementary. It depends on the exact change in the boundary conditions how the heat flows react, but showing one is enough. This is done in Fig. 11 for four ways to induce a step change in condition: by T_a , C_a , T_{sk} and C_{sk} , using the predictive model.

It is shown (for the conditions specified in Table II) that a step change in environmental condition evokes a smaller than proportional initial jump in the relevant skin heat flow, followed by a gradual change until the new equilibrium is reached. A step change in skin condition, in contrast, evokes a more than proportional initial jump, followed by a reversed transient. It is thus predicted that shocks in environmental temperature or humidity are damped by absorbing clothing, while there is an immediate response to a cooling requirement

from the skin. This could in part explain the common experience that during strenuous work in a varying environment absorbing clothing is more comfortable than non-absorbing clothing.

Cassie (1962) measured the heat loss from a "sweating" manikin and indeed found peaks in heat loss very similar to that of the bottom panel of Fig. 11, with the difference, however, that he was wetting the fabric with liquid, instead of with vapour so that the peak becomes visible in the total of Dry_{sk} and $Evap_{sk}$ as well.

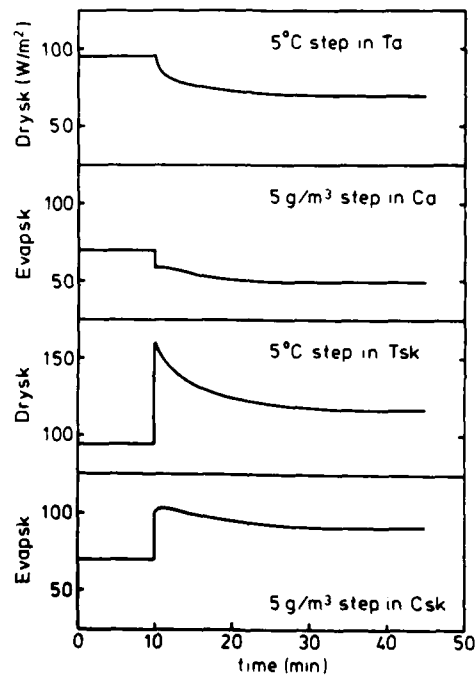


Fig. 11 The predicted response of Dry_{sk} following a step in T_a (top panel) and T_{sk} (third panel), and of $Evap_{sk}$ following a step in C_a (second panel) and C_{sk} (bottom panel) for the conditions specified in Table II.

De Dear et al. (1989) measured skin temperature and comfort votes of subjects wearing woolen and polyester garments, during up and down steps of the environmental relative humidity. Our model predicts that during an up-step the dry heat flow from the skin shows a dip which fades away with a time constant dependent on the absorption capacity

of the clothing. This would be reflected in a peak in skin temperature. That is exactly what De Dear et al. found. Skin temperature (2 subjects only) rose some few tenth of a degree C, falling again to a new level, resulting from the redistribution of metabolic heat over evaporative and dry heat loss. The associated thermal sensation is somewhat different: the peak following an up-step in environmental humidity is rather obscure, whereas the dip following a down-step is enhanced. De Dear et al. ascribe this to a difference in sensitivity for skin heating and skin cooling.

4 CONCLUSIONS

- The quantitative theory, describing the rate of dry and evaporative heat transfer in clothing during transient conditions, provides a satisfactory description of the observed heat flows and temperatures, despite the fact that the theory assumes clothing to be a single homogeneous layer, covered with a surface air layer. The characteristics of the clothing are defined in terms of heat transfer coefficient (h_{cl}), water vapour resistance (d_{cl}) and moisture absorption capacity.
- During transients in absorbing clothing the dry and evaporative heat flows from skin to clothing are different from those to the environment. In classical indirect calorimetry the latter are measured. Moreover, the values change in time. The sum of the dry and evaporative heat flow is the same inside and outside the clothing.
- Absorbing clothing tends to moderate the effect of a change in environmental condition on the heat flows at the skin, but enhances the effect of a change in skin condition.
- During desorption (thus with moist clothing) there is more heat stress than during absorption (with dry clothing).
- During transients the surface temperature and vapour concentration of the clothing change, following a linear relationship: when the temperature increases, the vapour concentration decreases, and the other way around.
- The time constant of this process is approximately $60/h_{cl}$ seconds per gram of moisture absorption capacity of the clothing.
- Since the heat flows observed in indirect calorimetry change in time, the accordingly calculated h_{cl} and d_{cl} change as well. The experiment should last three times the time constant to reveal the equilibrium (true) value. Before that moment the apparent values are

obtained. The apparent h_{cl} is linearly related to the inverse of the apparent d_{cl} .

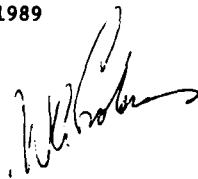
- When different environmental conditions are applied in a test with subsequent differences in heat strain, it should be recognized that uneven clothing distribution over the body may cause real differences in d_{cl} due to differences in sweat distribution.

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Date: October 5, 1989

Drs. W.A. Lotens



REPORT DOCUMENTATION PAGE		
1. DEFENCE REPORT NUMBER (MOD-NL) TD 89-1060	2. RECIPIENT'S ACCESSION NUMBER	3. PERFORMING ORGANIZATION REPORT NUMBER 12F 1989-32
4. PROJECT/TASK/WORK UNIT NO. 736.1	5. CONTRACT NUMBER 887-63	6. REPORT DATE October 6, 1989
7. NUMBER OF PAGES 33	8. NUMBER OF REFERENCES 13	9. TYPE OF REPORT AND DATES COVERED Final
10. TITLE AND SUBTITLE The effect of moisture absorption in clothing on the human heat balance		
11. AUTHOR(S) W.A. Lotens and G. Havenith		
12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) TNO Institute for Perception Kampweg 5 3769 DE SOESTERBERG		
13. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) TNO Division of National Defence Research Koningin Marijelaan 21 2595 GA DEN HAAG		
14. SUPPLEMENTARY NOTES		
15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE) A theory of moisture absorption in clothing, with the associated effects of heat transfer, was developed based on the assumption that clothing can be regarded as a moisture buffering capacitor enclosed between heat and vapour resistances, and covered with the adjacent air layer. The theory was checked with an experiment involving four subjects. They wore heavy woolen clothing, which was either initially dried or wetted, in both a warm and a cool environment. The experimental results confirmed satisfactorily the theoretical predictions that (1) the dry and evaporative heat loss will change in time and will both converge for the dry and moist garments to the equilibrium condition, (2) the clothing surface temperature and humidity are bound to a straight line on the psychrometric chart, (3) dry garments cause higher heat strain than wet garments, (4) the time course is predictable from the buffering capacity of the clothing and the heat transfer coefficient, and (5) the apparent heat and moisture transfer coefficients are bound to a linear relationship, revealing the true values only during equilibrium. Contrary to the expectation the observed vapour resistance is lower in the heat than in the cold, probably due to differences in sweat distribution.		
16. DESCRIPTORS Clothing Physiology Protective Clothing Perspiration Effects of Heat		IDENTIFIERS
17a. SECURITY CLASSIFICATION (OF REPORT) -	17b. SECURITY CLASSIFICATION (OF PAGE) -	17c. SECURITY CLASSIFICATION (OF ABSTRACT) -
18. DISTRIBUTION/AVAILABILITY STATEMENT Unlimited availability		17d. SECURITY CLASSIFICATION (OF TITLES) -

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