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VAPOUR TRANSFER IN 2-LAYER CLOTHING
DUE TO DIFFUSION AND VENTILATION

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Title: Vapour transfer in 2-layer clothing due to
diffusion and ventilation

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SUMMARY

An experiment was carried out to measure the vapour resistance of 2-layer clothing ensembles as a function of air permeability of the outer layer, open or closed apertures, wind, and walking, both for the total ensemble and for the outer garment alone. Six subjects walked on a treadmill (0., 2.5, and 5 km/h) which was placed in a wind tunnel (.2, .7, and 3.0 m/s). They wore long underwear and an outer garment made of impermeable (imp), microporous (mpo), low air permeable (loa), or high air permeable (hia) fabric. Vapour resistances were determined by a trace gas method which was calibrated against water vapour resistance. The vapour resistances of the underclothing and the outer garment were calculated and also the ventilation through the apertures. The vapour resistance of the underclothing was almost constant at 5 mm air equivalent. The ventilation was strongly dependent on wind and motion but still so low (54 l/min) that only the impermeable garment could noticeably benefit from it. The vapour resistance of the garments varied also strongly (imp 55-200 mm, mpo 12-20 mm, loa and hia 1-14 mm). For the imp garment this is due to leakage of air whereas the vapour permeable garments were dominated by the diffusion and air penetration through the fabric. It is concluded that ventilation with vents can not match the effect of vapour permeability, but that real low vapour resistances are only possible with air permeable fabrics.

Damptransport door diffusie en ventilatie van 2-lagen kleding

W.A. Lotens en L.J.A. Wammes

SAMENVATTING

Een experiment werd uitgevoerd om de waterdampweerstand van 2-laags
kledingcombinaties te meten, afhankelijk van de luchtdoorlaatbaarheid
van de buitenlaag, al of niet gesloten openingen, wind, en loopsnel-
heid, zowel van de gehele combinatie als van de buitenlaag apart. Zes
proefpersonen liepen op een loopband (0, 2,5, en 5 km/h) in een
windtunnel (.2, .7, en 3 m/s). Ze droegen lang ondergoed en een
regenpak van impermeabel (imp), microporeus (mpo), weinig luchtdoorla-
tend (loa), of goed luchtdoorlatend (hia) materiaal. De dampweerstand
werd bepaald met behulp van een tracergas-techniek die tegen waterdamp
werd geijkt. De dampweerstanden van de onderkleding en de overkleding
werden berekend, alsmede de ventilatie door de openingen. De dampweer-
stand van de onderkleding bedroeg bijna onveranderlijk 5 mm luchtequi-
valent. De ventilatie was erg afhankelijk van wind en beweging maar
altijd nog zo laag (54 1/min) dat alleen het impermeabele pak er
merkbaar van profiteerde. Ook de dampweerstand van de bovenkleding
varieerde erg (imp 55-200 mm, mpo 12-20 mm, loa en hia 1-14 mm). Voor
het pak imp kwam dit door de lucht die toch nog door de kleding lekt,
terwijl de dampweerstand van de dampdoorlatende pakken door de diffu-
sie en door de luchtpenetratie door de stof bepaald werd. De conclusie
is dat ventilatie niet opweegt tegen dampdoorlatendheid, maar dat
werkelijk lage dampweerstanden alleen met luchtdoorlatende stoffen
bereikt worden.

1   INTRODUCTION

Recently, Havenith et al. (1990) described the changes in clothing
vapour transfer due to motion of the wearer and wind of three types of
clothing. The use of a tracergas instead of water vapour enabled them
to collect more data than had been done until then in a single experi-
ment. The results showed that the vapour resistance was stronger
dependent on wind and motion than the heat resistance. This observa-
tion is in accordance with theoretical expectations. It was shown that
when the heat resistance is split into a convective and a radiative
part, the vapour resistance changes in the same proportion as the
convective part of the heat resistance. This is another example of the
Lewis relation, which had sofar been shown for air layers (Lewis
relation), for clothing layers in static condition (Woodcock, 1962)
and for clothing ensembles in static conditions (McCullough et al.,
1989), but not for clothing ensembles in dynamic conditions. The
difference between static and dynamic refers here to air motion, which
invokes ventilation in addition to diffusion.

Lotens and Havenith (1990) showed that the tracer gas measurements fit
well into the results of a number of studies reported in the litera-
ture on heat and vapour transmission through clothing and presented
regression equations for the calculation of vapour and heat resis-
tance. In fact, the vapour resistance is calculated from the insula-
tion using the aforementioned relationship. Although there generally
was a good fit, in particular impermeable garments did not fit too
well. This was one of the reasons to try to collect more data regard-
ing the influence of air permeability on vapour resistance.

Another reason was that in later papers (Lotens & Pieters, 1990;
Lotens et al., 1990) the regression model was substituted by an ana-
lytical model, distinguishing underclothing, trapped air, outer layer,
and adjacent air (Fig. 1a). This model proved to be successful in
predicting the heat transfer through a wide range of clothing and
environmental conditions. One of the important features of this model
is the ventilation of the trapped air through apertures in the cloth-
ing and right through the outer material. Regarding this ventilation
insufficient data are available, however.

Finally, the distinction of underclothing from outer clothing in the
model gave good overall results but little is known regarding the
properties of the separate layers. Therefore this distinction will be
made in this experiment. It was assumed that more layers of under-

clothing may be lumped together in a single layer without introducing serious errors. This was justified by comparison between experimental data and model predictions, which suggests that the vapour resistance of the underclothing shows less variation than that of the outer garment during wind and motion. This effect can be observed in the present test, but measurements with multilayer ensembles are beyond the scope of the present study.

Wind and walking speed are used to vary the ventilation, similar to the experiment of Havenith et al. (1990). The difference is that only one type of ensemble is tested (long underwear and two piece work suit), but with systematic variation of ventilation and air permeability of the outer garment, and that is looked into the contribution of the separate layers, whereas Havenith et al. only measured the total vapour resistance.

2   THEORY

In Fig. 1b a number of vapour resistances are distinguished in a four layer model of a clothing ensemble (Fig. 1a). The underclothing may comprise of one or more layers, that are lumped. The trapped air layer consists of two adjacent air layers and free moving air in between. From the trapped air layer ventilation causes a pathway for heat and vapour to the outside air. The other pathway carries vapour through the material and the surface air layer at the outside. The vapour resistances d are expressed in mm air equivalent (Whelan et al., 1955), which is the thickness of a still air layer that would have the same diffusion resistance. This unit is easy to comprehend, there are accurate methods available for its measurement on fabrics (Farnworth & Dolhan, 1984; Farnworth et al., 1990), and its mathematical treatment is simple. Mass transport m' by diffusion is defined by

$$m' = 1000 * D * dC/d \qquad (g/m^2 s) \qquad (1)$$

where D = diffusion coefficient   (25.10-6 m^2/s for water vapour in air)

dC = vapour concentration gradient (g/m^3)

d = air equivalent (mm)
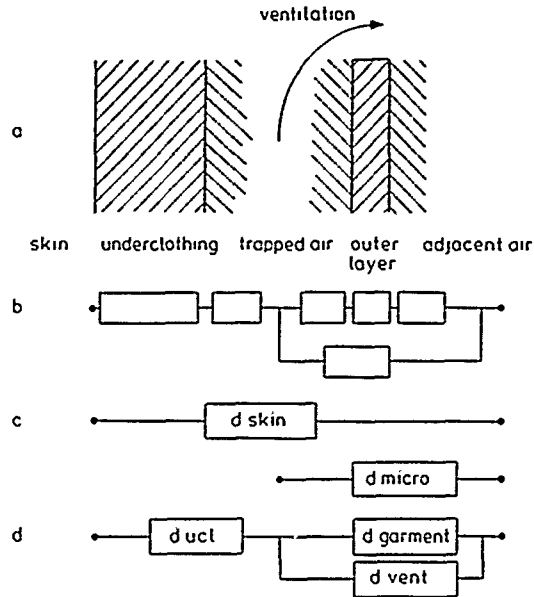
Fig. 1 A four layer clothing ensemble (underclothing, trapped air, outer garment, and adjacent air) which is ventilated (a). The various layers have a vapour resistance each (b). Two resistances are measured in the experiment (c). The vapour resistances of the underclothing (d_{ucl}), the ventilation (d_{vent}), and of the outer garment ($d_{garment}$) may be deduced (d).

For still air the air equivalent is by definition equal to the real thickness of the air layer. The same air layer forms the conductive heat resistance and consequently

$$d = 1000*\lambda/hc \qquad (mm) \qquad (2)$$

where λ = heat conductivity (.026 W/mC for air)
      hc = conductive heat transfer coefficient (W/m^2C)

Since the evaporative heat transport is given by

$$Evap = He*m' \qquad (W/m^2) \qquad (3)$$

where He = heat of evaporation (2430 J/g for water)
but according to the Lewis relation also by

$$Evap = L*hc*dC \qquad (4)$$

equating 3 to 4 and substitution of 1 and 2 reveals that

$$L = He*D/\lambda \qquad \text{(Lewis constant, } Cm^3/g) \qquad (5)$$

Substituting the given values results in $L = 2.34$ Cm^3/g ($= 2.2$ C/torr $= .0165$ C/Pa).

The mass transport of the ventilation is defined by

$$m' = Vent*dC \qquad (g/m^2s) \qquad (6)$$

where Vent = ventilation in m^3/s per m^2 of clothed body surface = m/s.

Although the ventilation process is intrinsically different from the diffusion process, the vapour resistance of the ventilation will be defined analogously to diffusion resistance (formula 1):

$$1000*D/d = Vent \text{ and thus } d = 1000*D/Vent \qquad (7)$$

The vapour resistances in Fig. 1b may be measured but the available measurement technique is not sophisticated enough to deal with each single resistance. Instead, two resistances may be measured, the total resistance and the resistance from the microclimate to the outside (Fig. 1c). The difference between the two is the resistance of the underclothing alone. By comparing garments with open and closed apertures the amount of ventilation through the apertures can be determined. Comparing garments with different air permeability also the effect of wind on the ventilation right through the outer fabric can be quantified. It is assumed that closing the apertures does not change the ventilation through the fabric. Thus the resistances of Fig. 1d can be determined.

3 METHODS

3.1 Tracer gas method

The tracer gas method used is basically the same as described by Havenith et al. (1990), but with improved equipment. The great advantage of this method over the use of sweating subjects is its speed. The absence of the long time constants involved in human sweat production and textile sweat absorption makes this method 20 times faster

than when using sweating subjects. The method involves argon, which is distributed over the skin by means of a perforated tubing system. In a dynamic equilibrium condition the concentration gradient is stable and the inflow equals the transport to the air. The mass balance equation can be used to calculate the ventilation:

$$\text{Vent} = \frac{\text{flow} * (C_{in} - C_{out})}{\text{area} * (C_{out} - C_{air})} \qquad \text{(m/s)}$$

where   flow = flow from the distribution system ($2.5 * 10^{-4}$ m^3/s)

      area = skin surface area covered by the distribution system (m^2)

      C_{in} = argon concentration in the distribution system (g/m^3)

      C_{out} = argon concentration at the location of measurement

      C_{air} = argon concentration in the air

The concentrations are measured with a mass spectrometer. Since only the ratio of concentrations is relevant no calibration of the instrument is required. The actual concentrations are between .01 and 10% over the argon concentration in air (~1%).

The concentration Cout is either measured at the skin or in the microclimate between clothing layers by means of a sampling tubing system. Fig. 2 shows the systems. The distribution system consists of 12 tubes of 6 mm diameter, perforated every 10 cm. All perforations are adjusted to yield $2.4 * 10^{-6}$ m^3/s of gas mixture. The length of the tubes and the location at the skin is such that a homogeneous distribution is obtained, each perforation serving .77% of the skin area. The total of 104 perforations thus apply to 80% of the skin area, leaving head, hands, and feet free. The sampling system is designed to be thinner and more flexible than the distribution system, in order to interfere as little as possible with the natural fit of the clothing. This is achieved by less and smaller tubes. The total of 8 tubes of 4 mm diameter contain 22 sampling perforations, equally distributed over half the clothing surface area. It is assumed that the ventilation is symmetrical over the body and the other half thus identical. Both systems are connected to a single pump, thus sucking nearly the same flow out of the clothing as is blown in. This avoids forced ventilation of the clothing.
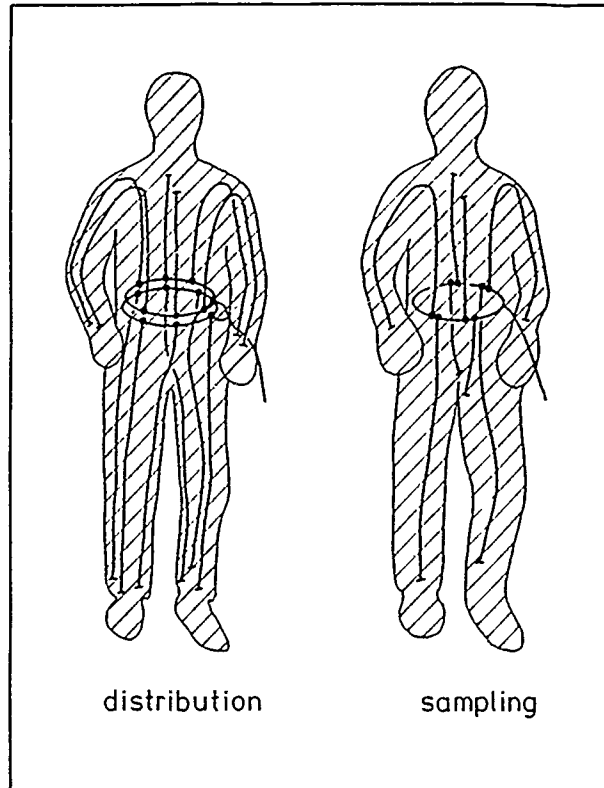
Fig. 2 Design of the distribution (left) and the sampling (right) harness.

The air equivalent is calculated with

$$d_{eq} = \frac{1000*\text{DA}_r}{\text{Vent}} \qquad (\text{mm})$$

where DA_r = diffusion coefficient for A_r (18.10^{-6} m^2/s)
The ventilation and vapour resistances in this paper refer to the clothing covered part of the skin only.

3.2   Calibration of ventilation

The validity of the method was tested by the measurement of the ventilation of a garment that was forced ventilated. An air impermeable garment was worn by two subjects at walking speeds of 0., 1.5, and 2.5

km/h. The apertures were tightened. By means of two 4 cm wide tubes air was blown underneath the jacket and the trousers, escaping through sleeves, legs, waist, and neck. The air flow was measured with a pneumotachograph and compared with the ventilation flow measured with the trace gas method. Fig. 3 shows that both flows are nearly equal. Without forced ventilation there is still diffusion, equivalent to $1.55*10^{-4}$ m/s (14 l/min) of ventilation. This value does not change with body motion, proving that motion induced ventilation was negligible in this test. With increasing forced ventilation the effect of diffusion must vanish since the air with low tracergas concentration close to the apertures will literally be pushed out of the clothing by the forced ventilation flow. It must therefore be assumed that the datapoints in Fig. 3 for $6.7*10^{-4}$ (60 l/min) or higher should be at the line of identity. This is actually true within the limits of confidence. The equipment appears to be more accurate than that of Havenith et al. (1990). This confirms the improvement of the design of the tubing systems, obtained by a more homogeneous distribution of the tracer gas. From theoretical considerations this was expected to be a major determinant of the accuracy (Lotens & Havenith, 1988).
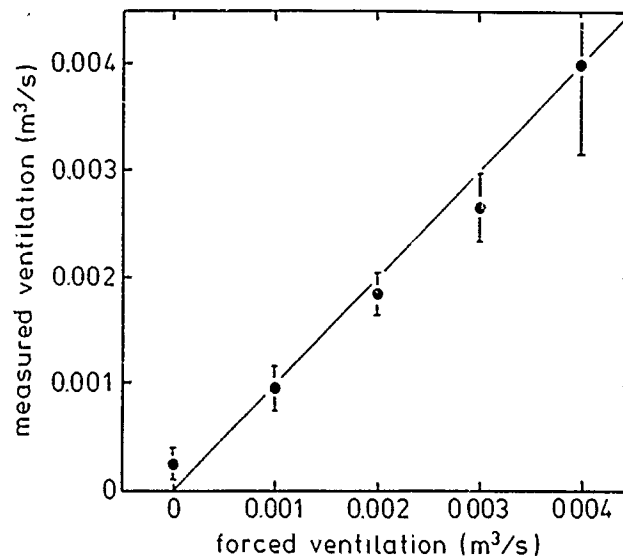

Fig. 3 Measured vs forced ventilation of an impermeable garment. The bars indicate confidence intervals.

3.3 Calibration of tracer gas resistance

The validity of the tracer gas resistance as a substitute for water vapour resistance was tested by measurement of the two simultaneously. A display manikin was dressed in long underwear and an overgarment, either impermeable or microporous. The underwear was instrumented with thermistors and wetted until soaking, avoiding drip, however. The water vapour gradient was determined from the saturatic . concentration at the underclothing temperature and the concentration in the air. The weight loss of the manikin was monitored continuously and the water vapour air equivalent calculated conform 1 by:

$$d_{H2O} = \frac{1000 * D_{H2O} * dC_{H2O}}{m'_{H2O}} \quad (mm)$$

where D_{H2O} = diffusion coefficient for H_2O in air (25.10^{-6} m^2/s)

dC_{H2O} = water vapour concentration gradient (g/m^3)

m'_{H2O} = rate of weight loss (g/m^2s)

The tracer gas air equivalent was measured in the earlier described way. Fig. 4 shows the calibration curve for the two garments and for various wind speeds. There is agreement between the two for high values of the air equivalent, but for low values the tracer gas value seems to underestimate the water vapour value. The reason for this discrepancy is that the spatial distribution of the tubing systems is still course for very high local ventilation (low d). It may be expected that deviations occur when the radial vapour transfer (through the clothing) is so large that the lateral vapour transfer (along the skin) fails to maintain a homogeneous vapour concentration in the microclimate. Since this problem could not be overcome rigorously with the available setup it was decided to use the line in Fig. 4 as a calibration line. All tracer gas air equivalents have thus been converted to water vapour air equivalents.
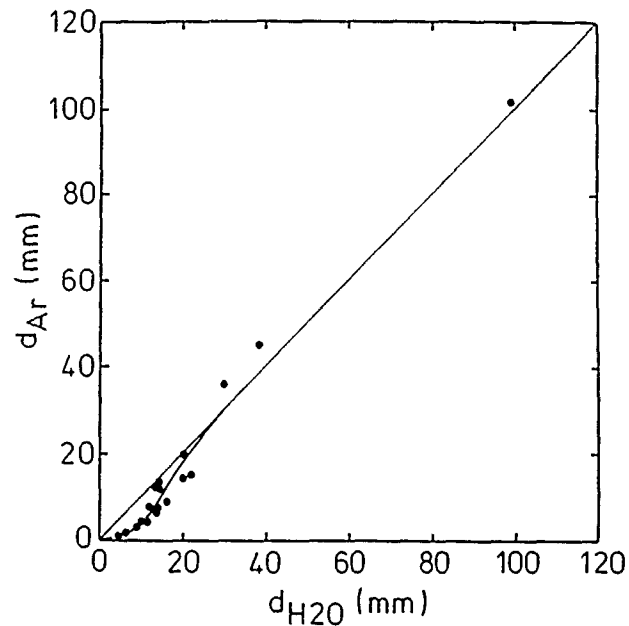
Fig. 4   The vapour resistance   measured with tracergas
(dA_r) compared to water vapour resistance (d_{H2O}), and the
used calibration curve.

3.4   Subjects

Six young male subjects participated in the study. This was a homo-
geneous group as to morphology, height 1.72 to 1.84 m, weight 71 to 79
kg, skin surface area 1.86 to 1.98 m^2. Skin surface area is calculated
according to DuBois and DuBois (1916).

3.5   Clothing

Four garments were worn, differing in fabric, but of equal design. The
garments were two piece rain wear, without hood, with adjustable
apertures (wrist, ankle, neck, and bottom of the jacket), covering 1.5
m^2 of skin area. They were worn over long cotton underwear. The fabrics
were of nearly equal flexibility and thickness but differed in air and
vapour permeability. The specification is given in Table I.

Table I Specification of the four clothing materials.

fabric	abbr	material	weight g/m^2	thickn. mm	d_{eq} mm	air perm $l/m^2 s$ @.2kPa
imper- meable	imp	pvc sheeting	228	.35	375	0
micro porous	mpo	coating on polyamid	160	.43	3.5	<.1
low air permea- bility	loa	polyamid plain weave	112	.46	1.5	170
high air permea bility	hia	cotton plain weave	144	.53	1.	590

The vapour permeability was measured with a diffusion meter of the design described by Farnworth et al. (1990). It was checked that the diffusion resistance of the microporous fabric is not specific for water vapour, but is the same for gases. To this purpose a crude test setup was build using CO_2. Air with a CO_2 concentration of 4.2% was blown into a small pan which was covered with the fabric. The air inside was circulated with a miniature fan. The CO_2 concentration was measured with a capnograph, which sucked an equal flow out of the pan as was let in. This was checked with an attached expansion bag. A small fan blew over the outside of the fabric. From the air flow through the pan and the measured concentration the diffusion resistance of the fabric together with the adjacent air layers can be calculated. Nearly the same d as with the diffusion meter was found when subtracting the vapour resistance of the air layers.

3.6   Experimental design

A complete design of subjects, garments, open or closed apertures, walking speeds, wind speeds, and locations of measurement was carried out. Subjects were instrumented with the tubing systems and wore the four garments successively. For each garment two blocks of nine conditions were carried out, one with closed and the other with open apertures. Each block comprised of standing and the walking speeds of 2.5 and 5.0 km/h, combined with the wind speeds of .2, .7, and 3.0 m/s. The first two garments were measured in the morning, the last two in the afternoon. For each subject the first day the ventilation at the skin was measured and the next day the whole procedure was repeated measuring the ventilation in the microclimate between the clothing

layers. Since only one subject at a time was measured the whole experiment lasted for the six subjects 12 days. For one subject one day was repeated to determine the reproducibility.

3.7 Statistics

Statistical tests were carried out using the SYSTAT package. Analysis of variance was performed and significant effects at the 1% level or better were subjected to a post hoc test to distinguish between levels within an effect.

4 RESULTS

In the Appendix the averaged data over the subjects for all 144 different conditions are tabulated. Fig. 5 shows the main effects of wind speed and walking both for the vapour resistance from skin to environment and from microclimate to environment.
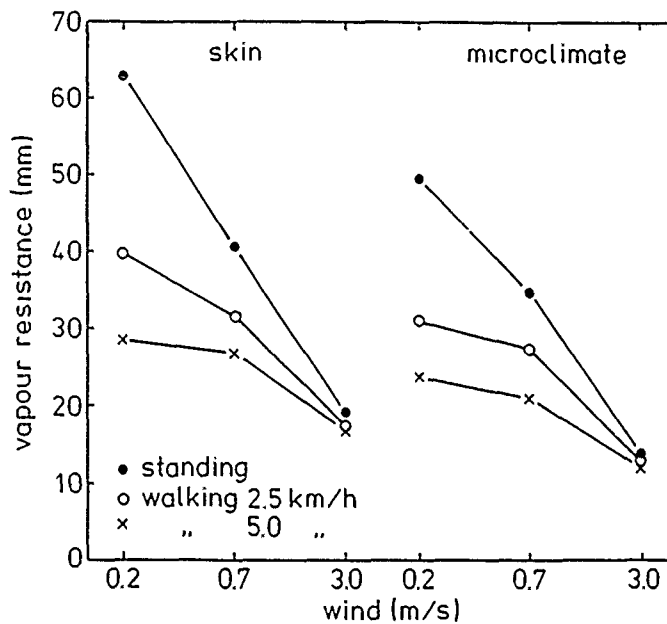
Fig. 5 Vapour resistance at the skin and in the microclimate as a function of wind and motion, averaged over subjects, garments, and open and closed apertures.

The effects of walking and wind are of the same magnitude but there is a strong interaction: at 3 m/s wind motion becomes irrelevant. In Fig. 5 there is averaged over garments, open or closed apertures, and subjects.

Fig. 6 shows the main effects of garments and wind speed on dskin. The vapour resistance is dependent on the wind speed for all garments, but garments differ widely in vapour resistance. For the wind speed of .2 m/s this is mainly due to diffusion but for the higher wind speeds due to differences in air penetration as well. The difference between the low and high air permeable garments is not significant. The effect of apertures is shown in Fig. 7 for the two most extreme garments. For the high air permeable garment opening of the apertures has no significant effect on d_{mi} but for the impermeable garment the effect is marked.
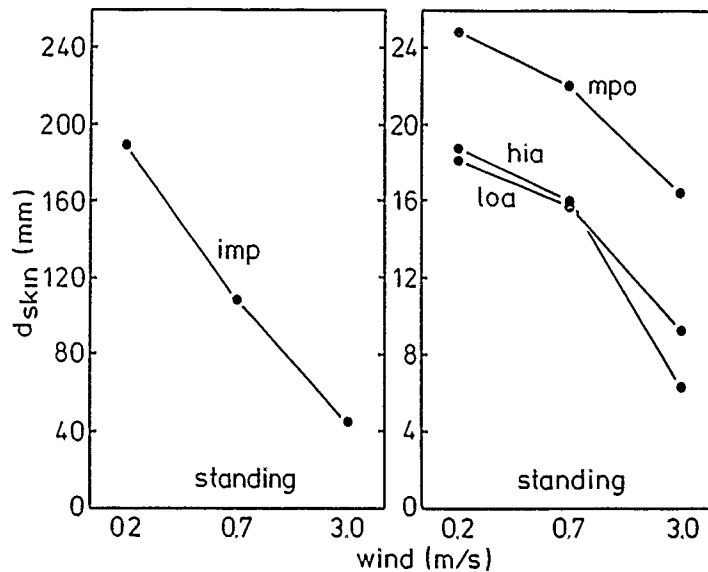
Fig. 6 The vapour resistance at the skin for the four garments as a function of wind, averaged over subjects and open and closed apertures.
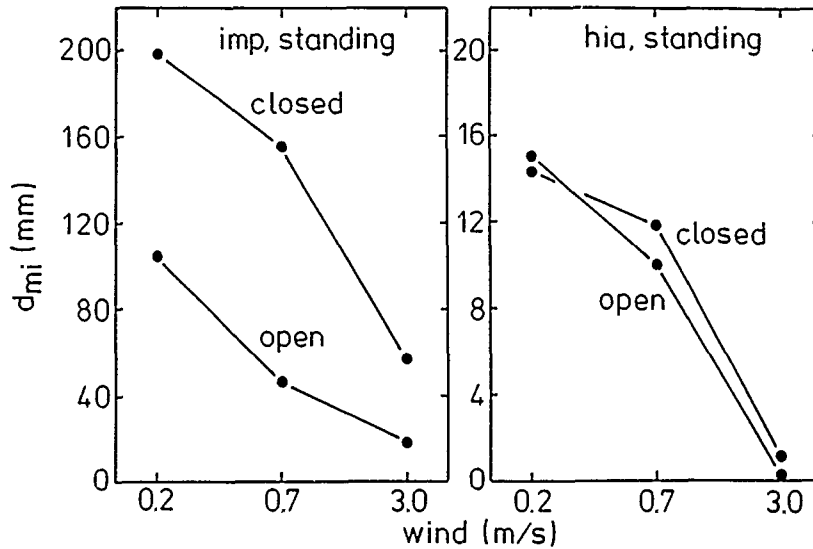
Fig. 7 Vapour resistance in the microclimate as a function of wind and apertures for the two extreme garments, averaged over subjects.

Both for d_{skin} and d_{mi} the effects are utterly significant, not only the main effects subjects, garments, apertures, wind, and walking speed, but also the single interactions and some double interactions. Differences between garments are subject dependent, garments differ in sensitivity for apertures, wind, and walking speed, and also the interaction between wind and walking speed is garment dependent. However, the difference between the garments loa and hia, and the effect of apertures on these two garments are not significant, and neither are their differences in wind and walking speed sensitivity. Over all garments 91% of the variance in d_{skin} and 95% of the variance in d_{mi} is explained by the mentioned factors. The strongest effects are the differences between garments (Fig. 6) and the difference in effect of opening the apertures between garments (Fig. 7), together good for 60% of the total variance in the experiment.

5   DISCUSSION

5.1   Underclothing

The vapour resistance of the underclothing (d_{ucl}) may be calculated from d_{skin} and d_{mi} by subtraction. For the impermeable garment the variance is too large to do so with acceptable accuracy. The average vapour resistance of the underclothing over subjects and garments varies between 4 and 5.7 mm, with a mean of 4.7 mm. The analysis of variance reveals that the differences between subjects and the inter-action between subjects and garments cause the largest part of the variance in d_{ucl}. The garments worn have a small but highly significant effect on d_{ucl} but opening the apertures has an insignificant effect. The wind sensitivity of the garments is highly significant on d_{ucl}. Comparing only the garments loa and hia the differences disappear. The independence of d_{ucl} of motion is surprising since internal convection might be expected. However, the enclosed air in the measurement is about 3 mm (the thickness of the underclothing is 2 mm), divided over two layers. Such thin layers are not easily disturbed. Also the wind effect is small.

5.2   Ventilation through the apertures

In Fig. 1d the pathways for vapour transfer were distinguished in transfer through the outer fabric and via the apertures. By comparison of open and closed apertures the two can be separated. For open aper-tures holds

$$d_{mi}(\text{open}) = \frac{d_{vent} * d_{garment}}{d_{vent} + d_{garment}}$$

whereas for closed apertures $d_{mi}(\text{closed}) = d_{garment}$. From these equations d_{vent} can be deduced:

$$d_{vent} = \frac{d_{mi}(\text{open}) * d_{mi}(\text{closed})}{d_{mi}(\text{closed}) - d_{mi}(\text{open})}$$

This calculation could be carried out for the garments imp and mpo with acceptable accuracy, but not for the garments hia and loa. For imp and mpo the results were largely identical. Fig. 8 shows d_{vent} as a function of wind and walking speed. Both these main effects and their

interaction are utterly significant. The difference between subjects was not significant.
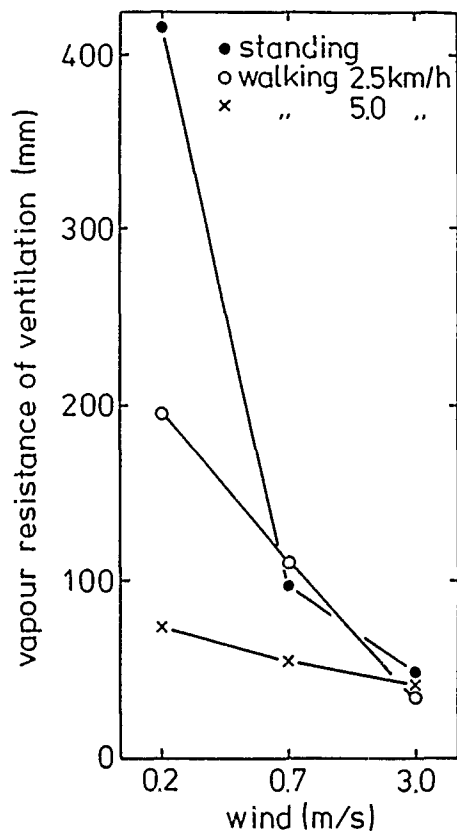
Fig. 8 Vapour resistance of the ventilation as a function of wind and motion.

The data show that the vapour resistance of the apertures of standing persons in quiet air is very high, but that walking 5 km/h or wind of .7 m/s decreases the vapour resistance to less than 100 mm, and wind and motion together to about 40 mm.

5.3   Vapour resistance of the outer garments

The vapour resistance of the outer garments (d_{ml} with closed apertures) is the most relevant variable to characterize the garments. The total vapour resistance in various conditions as to underwear and apertures can be deduced from $d_{garment}$ using d_{vent} and d_{ucl}, since the latter two

are hardly dependent on the garment worn. Fig. 9 shows $d_{garment}$ for the four garments in the experiment as a function of wind and walking speed. All garments show the same characteristic decrease in vapour resistance with increasing wind and motion, and a strong interaction. Due to motion and wind the vapour resistance of hia decreases to a level below the fabric vapour resistance, proving that air is penetrating the fabric. This is also true for the imp garment that true enough is air impermeable, but still has leaks at the zipper, seams, and imperfectly closed apertures.
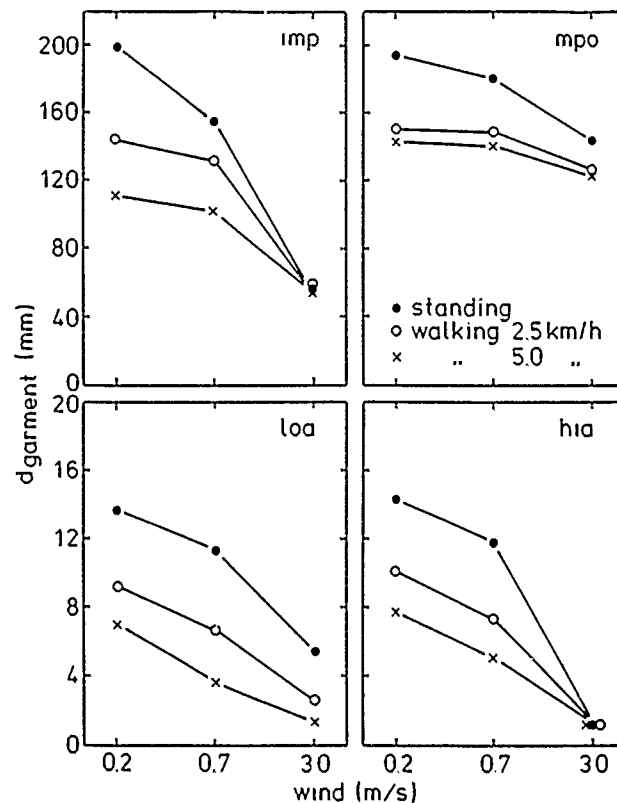
Fig. 9 Vapour resistance of the outer garments as a function of wind and motion.

Combining $d_{garment}$ with d_{vent} and d_{ucl}, it is clear that d_{vent} has only an appreciable effect on the total vapour resistance for the imp garment. Havenith et al. (1990) estimated that d_{vent} is of the same order $d_{garment}$ for an ensemble that could be compare to loa, when walking in wind. According to the new measurements the effect of d_{vent} is lower. The vapour resistance of the underclothing may contribute largely to the

total vapour resistance for the loa and hia garments. The difference in air permeability of loa and hia does not result in greatly different vapour resistances. The vapour resistance of the mpo garment, that is rather windtight, is dominated by its diffusion resistance and therefore relatively constant.

The statistical analysis shows that the effects of subjects, garments, wind, and walking speed are highly significant and so are the differences in wind and motion sensitivities of the garments, the interaction between subjects and garments, and between wind and motion, and even the difference in the latter interaction between garments. Comparing only the garments loa and hia there is no main effect anymore and also some interactions disappear, but there is still a highly significant difference in wind sensitivity.

5.4   Tracer gas method

Unlike the tracer gas methods published by other investigates the currently used method gives absolute values and allows the calculation of vapour resistances. Crockford et al. (1972) used the decay of tracer gas concentration after termination of the administration of gas. This provides ventilation ratios, which require the measurement of the ventilated volume to obtain absolute values. These volume measurements were carried out under artificial circumstances (Crockford and Rosenblum, 1974) and their accuracy is disputable. The method has not basically been improved.

Reischl et al. (1987) apply a method in which locally administered tracer gas is locally sampled. When there is relatively little lateral diffusion (such as in a single air layer) this method may be very useful in determining the mass transfer coefficient, but when used inside multilayer clothing ensembles serious interpretation problems rise as to the area for which the ventilation value holds. For the direct measurement of the convective heat transfer coefficient (proportional to the mass transfer coefficient) at the surface of clothing this method seems a promising alternative to the seldom used naphthalene sublimation method of Nishi et al. (1970).

In this study the same method was applied as by Havenith et al. (1990) but the harness was improved. This resulted in a calibration line for tracer gas with reference to water vapour that was nearer to the line

of identity and only required corrections for low vapour resistance
values.

5.5 Reproducibility

The accuracy of the method used in this study is largely determined by
the resolution of the mass spectrometer. Argon has been used for
various reasons, such as safety, lack of absorption, and inertness,
but has unfortunately a rather strong background spectrum in air. The
result is that high ventilations are less accurately measured. Venti-
lations of $1.3*10^{-3}$ m/s (70 $1/m^2$min) have a standard deviation of 6%
and ventilations of $5*10^{-3}$ m/s (300 $1/m^2$min) a standard deviation of
20%. The resulting standard error in d is about 10% with a minimum of
.5 mm.

The reproducibility of the experimental condition is often worse than
that of the method, in particular for static conditions. This may in
part be due to differences in donning. Wind and motion tend to stabil-
ize the fit of the clothing around the body and reduce the influence
of the trapped air. For one subject 72 experimental conditions were
reproduced, 18 for each garment. The mean difference between the
measurements was less than 1 mm with a standard deviation of 1 mm for
the garments mpo, loa, and hia, but -6 and 9 mm, respectively, for
garment imp. 9 mm compares to 8% of the actual value.

5.6 Comparison with other studies

The most detailed study that allows comparison of data is that of
Havenith et al. (1990). They measured the vapour resistance of three
ensembles as a function of wind and motion. Two ensembles compare more
or less with ensembles in this study. Their ensemble B comprised of
poloshirt, sweater, trousers, and cotton coverall, with comparable air
permeability to garment loa. The difference between the two ensembles
is probably the greater thickness of the underclothing in ensemble B.
The data of Havenith et al. have been converted to the values given in
this study (d_{skin}-open), since we did not include the uncovered skin in
the d-values. The wind and walking speeds were different in the two
studies but graphical interpolation shows that our data (5-18 mm) fit
within 10% with theirs (7-30 mm), with exception of the standing, low
air speed data, which are up to 7 mm higher in their study. This could
well be caused by the thicker underclothing.

Their ensemble C was similar to B but the coverall was impermeable. It compares with our ensemble imp. Using the same technique the fit between our data (10-120 mm) and theirs (11-150 mm) is also within 10%. Due to the high values the difference in thickness of the under-clothing is masked.

Lotens and Havenith (1988) measured the ventilation of an impermeable garment of comparable design as in this study, but with a number of adjustable vents. The ventilation was converted to vapour resistance. With the vents closed the vapour resistance ranged from 5 to 55 mm, for wind speeds of 0 to 6 m/s and the same walking speeds as in this study. Graphical interpolation shows that this is about half the vapour resistance of garment imp for all conditions. The reason might be the leakage through the many meters of loop and hook tape with which the covers of the vents were attached.

Holmér and Elnas (1981) measured the vapour resistance of three en-sembles during ergometer cycling (60 rpm) in quiet air. This condition compares to walking with .7 m/s (Lotens and Havenith, 1990). The ensembles worn were shorts with a coverall, worn with a semipermeable or an impermeable overgarment, or without an overgarment. The recalculated vapour resistances for the clothed area only amounted to 15, 50, and 11.5 mm, respectively. The comparable measurements in our study are d_{skin} (open apertures) for ensembles mpo and imp (regarding the coverall as underwear), and d_{ml} (open) for ensemble loa (no under-wear). These have vapour resistances of 17, 40, and 9.7 mm, respect-ively.

Lotens and Havenith (1990) gave a mathematical model to calculate clothing insulation and vapour resistance when the geometry is spec-ified and regression equations for the change of insulation and vapour resistance with activity and wind. These equations were based on literature data and do not include an air permeability parameter since this quantity was usually not specified. The calculations predicted for d_{skin} (open) a range of 260-95 mm for ensemble imp, 23-8 mm for mpo, and 19-7 mm for loa and hia, for the various wind and walking speeds. The measured values were in the range of 126-17, 25-13, and 19-5 mm, respectively. The calculation for the vapour permeable garments thus seems quite accurate, but for the vapour impermeable garment deviat-ing. The main reason for this deviation is that the vapour impermeable clothing shows a larger dynamical range than permeable clothing due to absence of the moderating effect of diffusion.

5.7   Ventilation, vapour permeability, and air permeability

Lotens and Havenith (1988) investigated the possibilities to increase the ventilation of an impermeable garment with by means of adjustable vents. With closed vents but open apertures the ventilation amounted at 5 km/h walking speed and 2 m/s wind to $2.2*10^{-3}$ m/s (200 l/min), equivalent to 11.3 mm of still air. Opening the vents and using a spacer under the garment to improve the internal circulation increased the ventilation to $4*10^{-3}$ m/s (360 l/min, 6.3 mm). This is probably the highest practical ventilation that can be obtained with impermeable fabric. With air permeable fabric the vents become superfluous since the ventilation increases under comparable circumstances to well over $11*10^{-3}$ m/s (1000 l/min, 2 mm, garments hia and loa). Garment imp, without the (closed) vents of that of Lotens and Havenith, showed $9.3*10^{-4}$ m/s (85 l/min, 27 mm). The microporous garment, which is hardly air permeable but has a low diffusion resistance, came under similar conditions to some 10 mm vapour resistance. The very best hydrophillic membranes, which are very permeable to water vapour (d=1 mm) but impermeable to air, will probably give an improvement of 2-3 mm due to lower diffusion resistance, but an unknown deterioration due to air impermeability.

It thus seems that under the specified circumstances the best vapour permeable but air impermeable garments have a factor two or three lower vapour resistance than vapour and air impermeable garments of a simple design (no vents, open apertures), and about the same vapour resistance as such garments with an optimized design. The vapour resistance of (low) air permeable garments is up to a factor of five lower, however.

6   CONCLUSIONS

- The better distribution of tracer gas of the improved method provides an accuracy of the determination of vapour resistance of 10% with a minimum of 1 mm. The calibration against water vapour might become superfluous with a still finer distribution.

- The method in this study allows the distinction between layers and the quantification of ventilation.

- The underclothing had an almost constant vapour resistance of about 5 mm, regardless of wind and motion.

- The ventilation through the apertures is highly dependent on wind and motion. Walking 5 km/h is about equivalent to wind of .7 m/s. The lowest vapour resistance of the apertures was still 40 mm and may by optimization of the design of the garment decrease to about 20 mm.

- The vapour resistance of the overgarments is dependent on wind and motion. The imp garment is in the range of 55-200 mm, mpo 12-20 mm, and both loa and hia 1-14 mm.

- There is agreement between the data of this and former studies.

- Ventilation through apertures and vents can not match the vapour transfer of good semipermeable materials, but much lower vapour resistances are obtained with (low) air permeable materials because of ventilation with penetrating air.
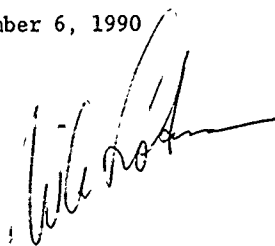
REFERENCES

Crockford, G.W., Crowder, M., and Prestidge, S.P. (1972). A trace gas technique for measuring clothing microclimate air exchange rates. British J. Ind. Med., 29, 378-386.

Crockford, G.W. and Rosenblum, H.A. (1974). The measurement of clothing microclimate volumes. Clothing Res. J., 2.3, 109-114.

DuBois, D. and DuBois, E.F. (1916). A formula to estimate the appropriate surface area if height and weight be known. Arch. Internal Med., 17, 863-871.

Farnworth, B. and Dolhan, P.A. (1984). An apparatus to measure the water vapour resistance of textiles. J. Text. Inst., 75, 142-145.

Farnworth, B., Lotens, W.A., and Wittgen, P.P.M.M. (1990). Variation of water vapour resistance of microporous and hydrophillic films with relative humidity. Text. Res. J., 60, 50-53.

Havenith, G., Heus, R., and Lotens, W.A. (1990). Clothing ventilation, vapour resistance and permeability index: changes due to posture, movement, and wind. Ergonomics (accepted).

Holmér, I. and Elnas, S. (1981). Physiological evaluation of the resistance to evaporative heat transfer through clothing. Ergonomics, 24, 63-74.

Lotens, W.A. and Havenith, G. (1988). Ventilation of rain wear determined by a trace gas method. In: Mekjavics, I.B., Banister, E.W., and Morison, J.B. (Eds), Environmental ergonomics. Taylor and Francis, New York, 162-176.

Lotens, W.A. and Havenith, G. (1990). Calculation of clothing insulation and vapour resistance. Ergonomics (accepted).

Lotens, W.A. and Pieters, A.M.J. (1990). Radiation heat load on clothed humans. Ergonomics (accepted).

Lotens, W.A., van de Linde, F.J.G., and Havenith, G. (1990). The effect of condensation in clothing on heat transfer. Ergonomics (submitted).

McCullough, E.A., Jones, B.W., and Tamura, P.E.T. (1989). A database for determining the evaporative resistance of clothing. ASHRAE Trans., 96/2.

Nishi, Y. and Gagge, A.P. (1970). Direct evaluation of convective heat transfer coefficient by naphthalene sublimation. J. Appl. Physiol., 29, 830-838.

Reischl, U., Spaul, W.A., Dukes-Dobos, F.N., and Hall, E.G. (1987). Ventilation analysis of industrial protective clothing. In: Asfour, S.S. (Ed.), Trends in Ergonomics/Human Factors IV. Elsevier Sc. Publ., North Holland.

Whelan, M.E., MacHattie, L.E., Goodings, A.C., and Turl, L.H. (1955). The diffusion of water vapour through laminae with particular reference to textile systems. Text. Res. J., 25, 197-223.

Woodcock, A.H. (1962). Moisture transfer in textile systems, part I. Text. Res. J., 32, 628-633.

Soesterberg, September 6, 1990

Drs. W.A. Lotens

APPENDIX

Vapour resistance (mm air equivalent) at the skin and in the microclimate as a function of open or closed apertures, wind speed, and walking speed for four clothing ensembles, impermeable (imp), microporous (mpo), low air permeable (loa), and high air permeable (hia).

wind	walking	d_{skin}				d_{mi}			
		imp	mpo	loa	hia	imp	mpo	loa	hia
open apertures									
.2	0.	126	25	18.4	18.9	104	19.1	14.6	15.
	2.5	40	17.4	14.1	14.2	36	14.3	9.7	10.1
	5	28	15.5	12.4	12.6	24	12.5	6.6	7.2
.7	0	57	21	16.1	15.5	47	15.3	10.1	10.
	2.5	34	16.8	13.2	12.9	32	13.2	6.2	6.2
	5	25	14.8	10.7	11.7	23	12.1	4.	4.
3.	0	20	14.4	7.9	5.3	18.3	11.7	2.9	.3
	2.5	16.9	14.1	7.	5.6	15.5	10.	1.9	1.1
	5	16.9	12.6	5.	4.7	15.8	9.	1.3	1.1
closed apertures									
.2	0	252	25	17.9	18.8	198	19.5	13.8	14.3
	2.5	183	18.3	14.2	14.	143	15.2	9.2	10.5
	5	118	16.2	13.	11.7	111	14.4	7.1	11.8
.7	0	157	23	15.5	16.5	155	18.1	11.3	11.8
	2.5	131	17.8	13.7	11.8	132	14.9	6.7	7.4
	5	113	16.5	11.9	11.3	101	14.1	3.7	5.1
3.	0	70	18.5	10.6	7.4	56	14.4	5.4	1.1
	2.5	65	16	8.8	7.1	58	12.7	2.6	1.2
	5	67	15.	8.2	5.6	56	12.4	1.5	1.2

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An experiment was carried out to measure the vapour resistance of 2-layer clothing ensembles as a function of air permeability of the outer layer, open or closed apertures, wind, and walking, both for the total ensemble and for the outer garment alone. Six subjects walked on a treadmill (0., 2.5, and 5 km/h) which was placed in a wind tunnel (.2, .7, and 3.0 m/s). They wore long underwear and an outer garment made of impermeable (imp), microporous (mpo), low air permeable (loa), or high air permeable (hia) fabric. Vapour resistances were determined by a trace gas method which was calibrated against water vapour resistance. The vapour resistances of the underclothing and the outer garment were calculated and also the ventilation through the apertures. The vapour resistance of the underclothing was almost constant at 5 mm air equivalent. The ventilation was strongly dependent on wind and motion but still so low (54 l/min) that only the impermeable garment could noticeably benefit from it. The vapour resistance of the garments varied also strongly (imp 55-200 mm, mpo 12-20 mm, loa and hia 1-14 mm). For the imp garment this is due to leakage of air whereas the vapour permeable garments were dominated by the diffusion and air penetration through the fabric. It is concluded that ventilation with vents can not match the effect of vapour permeability, but that real low vapour resistances are only possible with air permeable fabrics.

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