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determined by a trace gas method

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7. Ventilation of Rainwear
Determined by a Trace Gas Method

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1. Introduction

A well-known problem with the comfort of rainwear is the condensation of evaporated sweat inside the garment, which results in continually increasing wetness of the clothing. Under certain environmental and workload conditions this may be effectively counteracted by the use of vapour permeable materials, but in particular for hard work and in a cool environment this runs short in function (Havenith and Lotens, 1984). The alternative way for moisture dissipation is ventilation of the microclimate under the garment. A theoretical study was carried out (Lotens, 1987) to estimate the required ventilation, in addition to permeability, to avoid condensation in the garment. The conclusion was that for moderate work ventilation must amount to 450 l min\(^{-1}\), depending on the permeability of the fabric.

Are such ventilation flows achievable? One could try to investigate this indirectly by conducting an experiment with various designs of rainwear. The resulting wetness would be an indicator then for the sufficiency of the ventilation. Since ventilation is a function of body motion (Vogt et al., 1983) as well as wind (windchill!) this would involve a large number of conditions, in fact too large for a manageable experiment. Far better would be the use of a method that provides direct ventilation figures.

An obvious method would be the washing out of a trace gas, analogous to the dye dilution or heat dilution methods used to determine cardiac output. Such attempts have been made by Crockford et al. (1972). They exchanged the air under the garments for pure nitrogen and watched the oxygen level to restore the normal value of 21%. The time constant of this process can be converted to a ventilation rate.

At least two factors stain this basically elegant method. The first is that the washout process is not a simple first-order process and does not reveal unique time constants. Seemingly, the ventilation changes during the measurement. The second is that only ventilation rates (min\(^{-1}\)) result, which are meaningless without a value for the ventilated volume, since the ventilation flow (l min\(^{-1}\)) is the product of ventilation rate and ventilated volume (l). Crockford and Rosenblum (1974) published a method to determine the volume, but this method is rather artificial and not free of experimental problems.

In this report attempts to improve Crockford’s trace gas method are documented. The resulting instrumentation is described and the results of an investigation of limited size in the design of rainwear are reported. Finally, the obtained figures are compared to the aforementioned estimated requirements.

2. The trace gas method

Replication of Crockford’s decay curve method showed that the decay curves are not of a simple exponential shape, but reflect at least two or three time constants. This is understandable since clothing really consists of several coupled compartments, with different magnitude of ventilation. Crockford et al. (1972) used an ambiguous method to avoid this problem. They sampled the concentration by a harness of tubings underneath the underclothing, but the inlet is under the rainwear. This indeed seems to simplify the decay curve, but it is now unclear what is actually measured: the ventilation of rainwear or that of rainwear and underclothing together. We decided to leave the matter of time constants and try another approach, the mass balance. This method is essentially simple. When a trace gas is constantly entered under the rainwear the concentration in the microclimate increases until equilibrium is settled. In that situation the total mass of trace gas washed out by ventilation meets the inflow:

\[
\text{inflow} \times C_p = \text{vent} \times C_{out} \quad (g \text{ min}^{-1})
\]

where inflow is the flow of pure trace gas (l min\(^{-1}\)); vent is ventilation of the microclimate by fresh air (l min\(^{-1}\)); \(C_{out}\) is trace gas concentration in the microclimate (g l\(^{-1}\)); and \(C_p\) is the concentration of pure trace gas (g l\(^{-1}\)). Thus the ventilation may be determined from the measurement of inflow and \(C_{out}\).

Preliminary experiments with distribution of pure trace gas showed that the mixing was far from ideal. Clouds of the heavier trace gas seemed to drop out of the jacket, not only producing a noisy signal, but causing an erroneous mean value as well.

For this reason the trace gas was next premixed with air, to bring the concentration and specific density down to near the expected value in
the microclimate. This method gave satisfactory results. The required air was taken from the microclimate to avoid forced ventilation due to the method. In this way a circulation was established into which the trace gas was injected. The next trial was with distribution and sampling harnesses connected to the circuit (Figures 7.1 and 7.2). A miniature fan was used for the circulation. It showed, however, that the performance of the fan was too small to prevent flow fluctuations during body motions. Consequently a more powerful fan had to be used, but that one had to stand on a table instead of being carried. Two tubes (about 1 cm diameter) connected the fan with the harnesses. This set-up is the current product of this development.

The design of the harness is such that the trace gas mixture is distributed evenly over the body. To this purpose the number and length of the tubes were carefully adjusted to body size and surface area. The pressure-flow relationship for the various tubes has been determined by means of an empirical formula, covering our measurements on a wide range of tubes:

$$V = \frac{d^2 \cdot (3.3 - \log L) \cdot p^{0.54}}{572}$$  \hspace{1cm} (2)

where $V$ is flow (1 s$^{-1}$); $d$ is diameter (mm); $L$ is length (cm); and $p$ is pressure (cm H$_2$O). The tubes of the distribution system were all of the same diameter (4 mm inner size) and the pressure is the same for all tubes. The only factor relevant for the distribution of the flow is thus the term $(3.3 - \log L)$ in equation (2). In Table 7.1 the resulting relative flow is compared to the relative body surface area, showing that there is a close correspondence. Head, hands and feet are considered to be outside the rainwear.

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|}
\hline
Compartment & Number of tubes & Length (cm) & Relative flow & Relative area (%) \\
\hline
\textbf{Upper body} & & & & \\
Upper arms & 2 & 80 & 7.5 & 7 \\
Lower arms & 2 & 105 & 7 & 7 \\
Back & 2 & 55 & 8 & 8 \\
Chest & 2 & 55 & 8 & 8 \\
\hline
\textbf{Lower body} & & & & \\
Buttocks & 2 & 50 & 8.5 & 36 \\
Belly & 2 & 40 & 9 & \\
Upper legs & 4 & 50 & 17 & 18 \\
Lower legs & 2 & 90 & 14 & 13 \\
& +2 & 105 & 79 & 81 \\
\hline
\textbf{Hands} & - & - & & 5 \\
\textbf{Feet} & - & - & 7 & 7 \\
\textbf{Head} & - & - & & 100 \\
\hline
\end{tabular}
\caption{Dimension of the distribution harness and relative flow compared to relative body surface area.}
\end{table}
3. Theoretical analysis

Equation (1) is a simplification of what really goes on. In the first place an inflow of trace gas would push some air out of the garment and should be corrected for. And in the second place a garment is not one well mixed balloon but a structure of more or less well mixed compartments. Many compartments will thus be ventilated with microclimate air of the other compartments, instead of with fresh air. Both these arguments are taken into the account with equation (3):

\[(\text{inflow} + \text{circ})C_{in} + \text{vent}C_e = (\text{vent} + \text{inflow} + \text{circ})C_{out}\]  

where inflow is flow of pure trace gas (l min\(^{-1}\)); circ is circulating flow over the fan (l min\(^{-1}\)); vent is ventilation (l min\(^{-1}\)); \(C_{in}\) is concentration in the distribution harness (g l\(^{-1}\)); \(C_{out}\) is concentration in the sampling harness (g l\(^{-1}\)); and \(C_e\) is concentration in the immediate environment (g l\(^{-1}\)).

Figure 7.4 shows the flow system. Equation (3) represents the mass balance for the part of the garment under investigation. The terms at the left of the sign of equality represent the sources of trace gas and those at the right the drains. When equation (3) is solved for vent, equation (4) results:

\[\text{vent} = \frac{(\text{inflow} + \text{circ})}{1 - \frac{\text{vent}}{\text{C}_e}} \frac{\text{C}_{in}/\text{C}_{out} - 1}{\text{C}_{out}}\]  

Since the calculation of vent is dependent on \(C_e\), the actual ventilation (air exchange) is only known when all concentrations inside the garment (\(C_e\)) are known. However, it is not so much the air exchange as the mass transfer that is of interest. This mass transfer \(M\) (g min\(^{-1}\)) is:

\[M = \text{vent} \left(\text{C}_{out} - \text{C}_e\right) = (\text{inflow} + \text{circ}) \left(\text{C}_{in} - \text{C}_{out}\right) = \text{vent}_{eff} \times \text{C}_{out}\]  

Figure 7.4. Flows and concentrations of trace gas for a part of a garment.

The sampling harness is similar to the distribution harness. Tubes of both harnesses are mounted pairwise at the body, with a separation of about 7 cm. This is enough to allow adequate mixing. The total system is separated in a lower and an upper part, for the measurements of jackets and trousers separately. Head, hands and feet are excluded. Figure 7.3, finally, shows a scheme of the whole set-up. The actual measuring device is a mass spectrometer, which is a versatile and sensitive instrument.

The trace gas used so far is N\(_2\)O, an anaesthetic gas. Since it is rarefied down to levels lower than 100 ppm in the room air, there is no danger involved. Theoretically it would be good to use a trace gas with the same diffusion coefficient as water vapour. This requires a gas with a molecular mass close to that of water. Unfortunately all masses in that range show a considerable background level on the mass spectrometer, which masks the signal. Mass 20 (neon) would be feasible, but it is an inert gas and has quite different diffusion characteristics to water vapour. An alternative would be the use of CH\(_4\), measuring the radical CH\(_3^+\) as mass 15, but methane is highly explosive. For this reason we decided to keep on using the available N\(_2\)O. As long as convection processes dominate pure diffusion, which is usually the case, no errors will be introduced.
By means of equation (5) effective ventilation $v_{ent,eff}$ is defined as the ventilation that would give the same mass transfer as vent if the ventilation had taken place with fresh air. By substituting (4) in (5) $v_{ent,eff}$ can be calculated as:

$$v_{ent,eff} = (\text{inflow + circ}) \left( C_{in}/C_{out,i} - 1 \right) \quad (6)$$

For the determination it is apparently sufficient to measure the flows (constant during the experiment) and the ratio of inlet and outlet concentration. Thus calibration of the mass spectrometer is not required. This facilitates experimentation.

An important question is, whether summation of the various body parts is allowed. Experimentally, the average sample concentration is determined by:

$$C_{out} = \frac{\sum \text{circ}_i \cdot C_{out,i}}{\sum \text{circ}_i}$$

and the circulating flow by

$$\text{inflow + circ} = \sum (\text{inflow}_i + \text{circ}_i)$$

where $i$ denotes the $i$th compartment. The average effective ventilation is then, according to (6):

$$\overline{v_{ent,eff}} = \frac{\sum (\text{inflow}_i + \text{circ}_i) \left( C_{in} \sum \frac{\text{circ}_i}{C_{out,i} \times \text{flow}_i} - 1 \right)}{\sum \text{circ}_i} \quad (7)$$

The summation of the effective ventilation of the various compartments, however, is:

$$v_{ent,eff} = \sum v_{ent,eff,i} = \sum (\text{inflow}_i + \text{circ}_i) \left( C_{in}/C_{out,i} - 1 \right) \quad (8)$$

Expressions (7) and (8) are only identical when all $C_{out,i}$ are equal, in other words, when there are no concentration differences under the garment. This is generally not so, but the even distribution of trace gas is very helpful in this respect. A numerical analysis shows that concentration differences of a factor of 10 over large body parts may cause serious calibration errors (underestimation by a factor of 3) but for concentrations not further than a factor of 2 apart, errors of the order of 10% result. In view of the variability in the data between subjects, fit of clothing and adjustment of fastenings this is not a major problem. The option is still open to measure the concentration at the various body parts separately, but this laborious method is not yet justified.

4. Validity test

The validity of the method was tested by means of forced ventilation of a jacket. Care had to be taken that the distribution of the forced air flow was area weighted, since only in that situation does the real ventilation compare with the measured effective ventilation. The area weighting was approximated by a simple tubing system, which was connected to an air pump via a gas flow meter.

The measurements were first done on a static manikin. Figure 7.5 (left frame) shows that a linear relationship results between forced and effective insulation, with a slight overestimation of the forced ventilation. The initial 10 l min$^{-1}$ effective ventilation, without forced ventilation, represents the diffusion through seams, zipper, apertures, etc. The deviation from the identity may well be explained by errors in the area weighting of the forced air flow. This weighting becomes less critical when body motion is introduced, pumping the air under the jacket back and forth, thus improving the mixing. This was tried with a marching subject (Figure 7.5, right frame) wearing the jacket well tied up. Again, a linear relationship results, with a slight underestimation of the forced ventilation this time. Indeed the increased mixing changed the calibration. In neither case, however, are the deviations large. Taking into account that ventilation of clothing is highly variable due to fit, tightness of apertures, body motion, wind, etc., the agreement between forced and effective ventilation is satisfactory. Therefore, the enhanced trace gas method is adequate both in a qualitative and a quantitative sense.
5. Measurements on rainwear

The feasibility of the method was tested on an experimental garment, designed by the Fibre Research Institute, TNO. This garment is a conventional two piece rainsuit made out of air impermeable fabric, provided, however, with a number of vents that can be opened or closed at will (Figure 7.6). In an earlier study (Lotens, 1984) it was shown that the design of vents with special aerodynamic properties (either due to wind or to pumping by body motion) is difficult, if not impossible. The major factor seemed to be the space under the garment, the design of the vent did not matter so much. For this reason in the experimental suit of this study the simplest possible design was chosen: a hole with a mesh.

Five subjects participated in three experiments with the following aims:

1. To investigate the combined effect of three speeds of walking (0, 2.5 and 5 km h\(^{-1}\)) and three wind speeds (0, 2 and 6 m s\(^{-1}\)) on ventilation.

2. To investigate the ventilation effect of the seven locations of vents on the jacket and the five locations on the trousers.

3. To investigate the ventilation effect of a spacer (about 4 cm wide) under the jacket, with and without the vents opened.

During the experiments the circulatory flow was constant at 26.4 l min\(^{-1}\) and the trace gas flow (inflow) was 0.11 l min\(^{-1}\). This resulted in an inlet concentration of 0.4% and a sample concentration in the magnitude of 0.01–0.1%. These concentrations are easily detectable with the mass spectrometer.

![Figure 7.7](image-url)

*Figure 7.7. Ventilation of jacket and trousers as a function of walking speed and wind speed. Vents were all closed.*

Figure 7.7 shows the results of Experiment 1. Two subjects were used for the measurements for the jacket and two others for the trousers, with all vents closed. The subjects walked on a treadmill in a wind-tunnel with the wind directed to their front. When the subjects were standing in still air ventilation was quite low, 10 l min\(^{-1}\) for the jacket and 30 l min\(^{-1}\) for the trousers. This basic ventilation is likely to be due to diffusion. A pilot experiment with a jacket of semipermeable material showed ventilations over 50 l min\(^{-1}\) under the same conditions, reflecting the additional diffusion through the fabric.

Ventilation increases due to motion, but even more due to wind. For wind speeds over 2 m s\(^{-1}\) the motion effect drowns in the wind effect. This is less so for the trousers which are already ventilated by the wind that is produced by the slinging motion of the legs. For the purpose of
dissipation of moisture, the motion pump is much more adequate than the wind. Violent motion is usually associated with high sweat production and due to the increased ventilation, the dissipation increases with the demand. Wind, however, is uncorrelated with the demand for dissipation and therefore often undesired. From this point of view a ventilation of 60 l min\(^{-1}\) for the jacket and 150 l min\(^{-1}\) for the trousers is the best achievable for this design. The two subjects did not noticeably differ in their experimental results.

Table 7.2 lists the average effects of the vents in Experiment 2. Vents were always open at both sides of the garment and the data thus pertain to two vents in symmetrical position. The increase in ventilation ranges roughly from 15–65 l min\(^{-1}\) for the jacket and 40–50 l min\(^{-1}\) for the trousers. The majority of the vents are in the range 40–60 l min\(^{-1}\). Exceptions are vents c and d, located at the stomach and under the arms respectively. An obvious explanation for their poor function is their location to the already ventilating bottom of the jacket. The highest ventilation is found for vents c and d, both located at the back. The other vents are all in the same range.

<table>
<thead>
<tr>
<th>Jacket</th>
<th>Ventilation (l min(^{-1}))</th>
<th>Trouser Ventilation (l min(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed</td>
<td>56</td>
<td>Closed</td>
</tr>
<tr>
<td>Vent a open</td>
<td>102</td>
<td>vent a open</td>
</tr>
<tr>
<td>b</td>
<td>69</td>
<td>i</td>
</tr>
<tr>
<td>c</td>
<td>71</td>
<td>j</td>
</tr>
<tr>
<td>d</td>
<td>98</td>
<td>k</td>
</tr>
<tr>
<td>e</td>
<td>119</td>
<td>l</td>
</tr>
<tr>
<td>f</td>
<td>119</td>
<td>g</td>
</tr>
</tbody>
</table>

Just a few data were obtained with combinations of vents. In all cases the combination provides less ventilation than the sum of the two separate vents. This seems logical because opening another vent would cause ventilation of already ventilated microclimate air. The data do not allow analysis of vents that are close to each other in contrast to well separated vents. Following the above reasoning this should make some difference.

The effect of the spacer (Experiment 3) is shown in Table 7.3. The spacer should probably be regarded as an enhancing rather than an additive factor, since no additional avenues of ventilation are opened. The spacer merely enables more circulation under the jacket. The magnifying factor is rather varying for the different designs, ranging from 1.4 to 2.2. The effect is largest for the closed suit, where the ventilation is most restricted.

### Discussion

Crockford et al. (1972) measured the ventilation rates of various designs of rainwear. A single raincoat offered ventilation rates of about 6 min\(^{-1}\) while sitting in a 2 m s\(^{-1}\) wind. The next best design was a duck suit with bopped trousers, which may give less ventilation than our waist-high trousers. They found exchange rates of about 3 min\(^{-1}\) for a hauling task in a 1.65 m s\(^{-1}\) wind. In a later publication (Crockford and Rosenblum, 1974) they estimated the volume of the garment at 2.3 l, multiplying to a ventilation of ~70 l min\(^{-1}\). This seems somewhat less than our results, although the task and clothing are too different to be certain about this. Opening wrist and ankle cuffs made a difference of about 25 l min\(^{-1}\) which is again a bit less than we found for the various vents (during walking).

Shivers et al. (1977) used the same method as Crockford. They measured ventilation rates for women's raincoats of 4 min\(^{-1}\) during rest and 8 min\(^{-1}\) during walking in quiet air. In particular, during rest there was a marked effect of belting—increasing the ventilation rate. This must be due to the decreased microclimate volume. No difference was found between a set-in sleeve and a low dolman sleeve. The lack of data about the microclimate volume prevents comparison with our results, but they compare roughly to Crockford's raincoat.

Both these studies prove how important it is to know the ventilation in absolute flows instead of as ventilation rates. In this respect, the current method is an improvement.

The trace gas method may also be applied to permeable clothing, but care has to be taken in interpreting the data. Many fabrics will pass the trace gas in the same way as they pass water vapour, by convection and diffusion. Hygroscopic materials, however, may pass water in other ways as well, for instance by wicking and on a molecular basis in hygroscopic films. These processes will not be simulated by the trace gas method.

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**Table 7.3. Ventilation (l min\(^{-1}\)) effect of the spacer worn under the jacket. Average over three subjects.**

<table>
<thead>
<tr>
<th>Without spacer</th>
<th>With spacer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed 56</td>
<td>125</td>
</tr>
<tr>
<td>Vent a open 102</td>
<td>174</td>
</tr>
<tr>
<td>e 71</td>
<td>111</td>
</tr>
<tr>
<td>f 110</td>
<td>156</td>
</tr>
</tbody>
</table>
6. Functional design of rainwear

We have shown above that a two-piece garment, provided with vents in both the jacket and the trousers and with a special provision to keep a space under the jacket may give a ventilation of:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>jacket</td>
<td>170</td>
</tr>
<tr>
<td>trousers</td>
<td>190</td>
</tr>
<tr>
<td>total</td>
<td>360 l min(^{-1})</td>
</tr>
</tbody>
</table>

This might increase a bit with an increasing number of vents. It is not likely, however, that a garment with many vents is really waterproof. Experience shows that any seam that is not adequately taped forms a leak during sustained rain. The more complicated the construction of the clothing, the higher the risk that leaks show up. Another problem is that rainwear may be used in such a variety of postures, depending on the application. In particular, military rainwear may be used in situations where rain will penetrate through the vents. Spacers are not available with commercial rainwear, to our knowledge. They would certainly increase the pack volume and therefore rarely be applied. For these reasons the figure of 360 l min\(^{-1}\) must be regarded as an optimistic maximum ventilation for rainwear. Is this a sufficiently large quantity? Figure 7.8, reproduced from Lotens (1987), gives the theoretical requirements for a moderately hard working person. These requirements are dependent on the vapour permeability of the fabric. Lower limits are presented for the ventilation and permeation together, that will prevent condensation of vapour on the inner face of the rainwear, according to the calculations.

The permeation is expressed in the permeability index \(i_m\) (Woodcock, 1962). The best rainwear materials available have an \(i_m\) of 0.16, but many good materials fall in the range 0.03-0.06. Lower \(i_m\) values may be found in less sophisticated (and less expensive) materials.

Figure 7.8 shows that in the cold (when condensation is more likely to occur than in the heat) even optimal ventilation is not sufficient to keep the rainwear of a moderately hard working person free of condensation, but in cool or warm environments ventilation probably can do. When ventilation is insufficient, permeation is required as well. According to Figure 7.8, for moderately hard working people fair permeability together with optimal ventilation is sufficient. Permeability alone, on the other hand, is sufficient only with the best materials. Rainwear made out of still good fabric may require up to 150 l min\(^{-1}\) of ventilation. For harder work, the requirements increase to a level that cannot be met by design and fabric technology.

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7. Conclusions

The enhanced trace gas method presented here is a convenient method. When effective ventilation is the variable of interest, the experimental procedure is fast and uncomplicated. A further advantage is that the result is expressed in 1 l min\(^{-1}\) in contrast to the ventilation rates in previously published methods. No assumptions about the actual process of ventilation are required, but care must be taken that the trace gas concentrations under the garment do not vary too much over the body, because averaging would not be allowed then.

The experimental suit clearly showed ventilation due to the motion pump, but this effect is drowned in the ventilation due to external wind for wind speeds over 2 m s\(^{-1}\). The trousers are less sensitive to wind than the jacket. Vents may increase the ventilation (at 5 km h\(^{-1}\) walking, 2 m s\(^{-1}\) wind) by some 40–60 l s\(^{-1}\), but somewhat less for vents low on the jacket. The effect of vents may be enhanced by a factor of 1.4–2.2 by introducing an air gap under the garment (4 cm wide) depending on the ventilation already present. Altogether a ventilation of 360 l min\(^{-1}\) is an optimistic maximum for carefully designed rainwear.
This ventilation would often be sufficient to keep the rainwear of moderately hard working persons free of condensation. For harder work permeability of the fabric is also required.

Acknowledgement

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References


8. Simple Relationships among Current Vapour Permeability Indices of Clothing with a Trapped-air Layer

Takahumi Oohori, Larry G. Berglund and A. Pharo Gagge

1. Introduction

The permeation ratio of clothing is particularly important for clothing studies, because it is not easy and sometimes expensive to measure evaporative insulation of clothing directly. If the permeation ratio is known in advance, one can calculate the evaporative insulation of clothing from the thermal insulation and the permeation ratio of clothing.

The purposes of our study are to analyse and compare three current indices of evaporative heat exchange through clothing, namely, $t_a$ for clothing, $t_r$ for outer-air and $t_m$ for combined clothing and air layers; and to incorporate explicitly the trapped air between skin and clothing into heat and mass transfer models.

2. Dry and evaporative heat transfer

We begin the present study with an analogy between dry and evaporative heat transfer from skin to ambient air. Heat transfer coefficients are described in two different formats, namely a resistance format and the Burton/Chatt conduction format. By using a resistance format, the dry heat transfer coefficient is expressed as the reciprocal of the sum of the air ($I_a$) and clothing ($I_c$) insulations:

$$\text{Dry/} \Delta T = 1/(I_a + I_c) \quad (\text{W K}^{-1} \text{ m}^{-2})$$

(1)