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The interaction of clothing ventilation with dry and evaporative heat transfer of jackets: the effect of air and vapor permeability

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Review

**The Interaction Of Clothing Ventilation With Dry And Evaporative Heat
Transfer Of Jackets – The Effect Of Air And Vapor Permeability**

Abstract:

Purpose: This paper aims to investigate the effect of air and vapor permeability of jacket materials on ventilation, heat and moisture transfer.

Design/methodology/approach: Clothing ventilation (V), thermal insulation (I) and vapor resistance (R_e) of three jackets made of different materials (normal textile, PVC and ‘breathable’ membrane coated textile), worn on an articulated thermal manikin in a controlled climate chamber, were measured under various conditions respectively. The various conditions of microenvironment ventilation were created by making the manikin stand and walk, combined with three wind speeds of < 0.2 , 0.4 and 2.0 m/s respectively.

Findings: In the condition without any forced convection, the air permeability makes no big difference to dry and evaporative heat transfer among the jackets, while the vapor permeability plays a big role in the evaporative heat loss. In the condition with forced convection, the dry heat diffusion is strongly coupled to the evaporative heat transfer in air and vapor permeable textile material.

Research limitations/implications: The effects of ventilation on heat and moisture transfer varies because of different ways of ventilation arising: penetration through the fabric is proven to be the most effective way in vapor transfer although it does not seem as helpful for dry heat diffusion.

Originality/value: The achievements in this paper deepens our understanding of the process of the dry and evaporative heat transfer through clothing, provides clothing designer guidance to choose proper materials for a garment, especially work clothing.

Keywords: air permeability; vapor permeability; clothing ventilation; thermal insulation; vapor resistance

INTRODUCTION

The vapor resistance of clothing together with its insulative property are important parameters in the calculation and prediction of a person's heat strain when working in a warm or hot environment. ⁽¹⁾ They are the two most important parameters in thermal environmental engineering, functional clothing design and end use of clothing ensembles. The thermal insulation and moisture vapor resistance can be measured by taking measurements on human subjects. The partitioned calorimetry method has been used to determine the clothing insulation and vapor resistance values. ⁽²⁻⁴⁾ This method gives realistic results, but requires sophisticated equipment and is time consuming, and the measured values may also exhibit substantial variability. Human-shaped thermal manikins which can simulate the heat and mass (water vapor) transfer between human body and environment have been developed for determining clothing insulative value directly. They are electrically heated and divided into several (up to 36) individually controlled segments. ⁽⁵⁾ Some sweating thermal manikins can even simulate gaseous perspiration by moisture transfer through a 'skin' made of a breathable fabric and the vapor resistance of clothing ensembles can be measured directly as well as the thermal insulation. ^(6,7)

Since the vapor resistance (R_e) is strongly linked to the microclimate ventilation beneath clothing (air change with the surrounding environment), the vapor resistance can also be

determined indirectly by measuring clothing ventilation.⁽⁸⁾ Two methods for measuring clothing ventilation have been developed in the past: one by Crockford et al.⁽⁹⁾ [CR] and one by Lotens and Havenith⁽¹⁰⁾ [LH], both using tracer gases to replace water vapor. Limitations to the methods, when used to calculate vapor resistance, could be posed by the assumptions made about the behavior of the tracer gas in relation to that of water vapor, in terms of diffusion and convection. The convective vapor heat transfer coefficient $h_{e,convection}$ is independent of the gas used for the measurement, while the coefficient due to water molecular diffusion in air $h_{e,diffusion}$ is dependent on the diffusion constant of the specific gas.⁽¹¹⁾ Thus the latter will be different between water vapor molecules and other gases used to replace these in the measurement methods. Lotens and Havenith used argon as trace gas because its diffusion coefficient is relatively close to that of a water molecule.

The materials, design and combination of clothing, body posture and movement, and wind are all influential on the ventilation of the microenvironment, thus on the insulative and vapor resistance properties of clothing ensembles.^(2, 8, 12-16) The ventilation arises in three ways: by penetration through fabrics, by natural convection through openings, or by pumping effect resulting from body movements forcing air around the clothing microenvironment out/in and through openings through vents, cuffs and collars. Material properties affecting heat and moisture diffusion through fabric are air and vapor permeability. Ueda and Havenith found that the air permeability of clothing materials affected ventilation significantly.⁽¹⁷⁾ Lotens and Wammes found that diffusion and air penetration strongly affected vapor transfer through clothing.⁽¹⁸⁾ To estimate the effect of body motion and wind on clothing thermal properties, some manikins were developed to be movable. They may be used in simulated wind conditions to

determine the reduction of thermal resistance and vapor resistance due to wind and walking effects.

The permeability index i_m is obtained through the Lewis relation between the evaporative heat transfer coefficient and the convective heat transfer coefficient. ⁽¹⁹⁾ It is dimensionless and has a theoretical range from unity (for the ideally permeable system) to zero (for the completely impermeable one). In practice, a slightly different definition tends to be used, using the total dry heat transfer coefficient (radiative and convective) instead of the convective only. This allows the use of the dry heat resistance and the evaporative heat resistance as measured on a person or manikin directly, rather than needing a split between convection and radiation. The consequence is that the maximum value is less than one, however. ^(8,11) It is felt that i_m is a more satisfactory term to describe moisture permeability than R_e . By measuring the insulation value, evaporative resistance, and permeability index of 22 representative clothing ensembles with a thermal manikin, McCullough et al. found that for most garments the i_m value was around 0.38. ⁽²⁰⁾ By using this constant value of i_m , the evaporative resistance values can be estimated from the insulation value for the ensemble in static conditions. However, in dynamic conditions with body movement or wind, the i_m value increases. The increase in i_m reflects the difference in the change of heat resistance compared to vapor resistance when a body starts to move or when wind is added. Since heat diffusion is the combination of convection and radiation, Havenith et al. tried to separate the convective and radiative heat resistance, and proposed a new vapor permeability index based on the convective heat resistance, which was said to remain constant as the ventilation changed with movement and wind. ⁽⁸⁾

The aim of this study is to investigate the effect of material properties on clothing ventilation, and heat and vapor transfer. The thermal insulation and vapor resistance were

measured using an articulated thermal manikin and the manikin was also equipped with a trace gas system to determine the ventilation simultaneously. ⁽²¹⁾ The relationship between the ventilation and thermal insulation and vapor resistance was quantified under various conditions of microenvironment ventilation, created by choosing garments of different materials, making the manikin stand and walk, combined with change of ambient air movement respectively. The change of permeability index with movement and wind was also discussed.

METHODS

Clothing ensembles

Tops: to investigate the effect of materials on ventilation, three jackets of same style but made of different materials were used for the study. Jacket TEX was made of a normal textile material (100% polyester) and thus was air and vapor permeable; Jacket PVC was made of PVC material, waterproof and air impermeable, and Jacket MEM was made of a special ‘breathable’ membrane coated textile material, waterproof, air impermeable and vapor permeable. A long sleeve T-shirt and jeans were used as underwear and bottom for the jackets.

Measurement of clothing thermal insulation and vapor resistance

The thermal insulation I_t and vapor resistance R_e for the jackets were obtained by using an articulated thermal manikin, Newton (Measurement Technology Northwest, Seattle, USA) according to ISO 9920: 2007. The manikin consists of 20 independently controlled thermal zones and has a tight-fit 100% cotton layer as its skin. The manikin skin temperature was set at 35°C. The ambient temperature and relative humidity were set as 20.5±1°C and 40±10%RH for V and I_t measurement, and 28±1°C and 40±10%RH for R_e measurement. For R_e tests, the skin was evenly wetted with a water sprayer before the tests started. Heat losses in the R_e determination were

corrected for dry heat loss in the test. For each zone, I and Re were calculated by using these equations:

$$I = \frac{T_{skin} - T_{amb}}{Q/A} \quad (1)$$

$$Re = \frac{(P_{sat} - P_{amb})}{\frac{Q}{A} - (T_{skin} - T_{amb})/I} \quad (2)$$

Where, T_{skin} , zone average temperature; T_{amb} , ambient temperature; Q/A , area weighted heat flux (W/m^2); P_{sat} : saturation vapor pressure at skin temperature (Pa); P_{amb} , vapor pressure at ambient temperature (Pa). The total thermal insulation and vapor resistance for the jackets were obtained with the parallel method using the following equation:

$$R_{wtd} = 1 / \sum \left(\frac{A_i}{A_{tot} * R_i} \right) \quad (3)$$

Where, R_i , zone resistance (Re or I); A_i , zone surface area; A_{tot} , total surface area.

Measurement of clothing microenvironment ventilation

A tracer gas system was used on the manikin to measure the ventilation on the body surface and argon was used as the trace gas.^(10,11) Air mixed with trace gas was blown into the clothing microclimate through a distribution tubing system, which was placed underneath the T-shirt to obtain as even as possible distribution of argon over the upper body surface. The sampling tubing system was placed similarly to the distribution one to suck air from the microclimate. The concentration of trace gas in air was measured by a mass spectrometer (Spectra, Crewe, UK). The ventilation rate of the clothing microenvironment over the upper body with the surrounding environment (V) was calculated by using the following equation according to Havenith et al.⁽⁸⁾.

$$V = (\text{circulating flow} + \text{trace gas flow}) \times \frac{(C_{in} - C_{out})}{(C_{out} - C_{amb})} \quad (l/min) \quad (4)$$

Here, V and flows are in l/min ; C_{in} , C_{out} and C_{amb} are argon concentration in ingoing air, sample air and ambient air respectively. The circulation flow was about 10 l/min, and pure argon (flow rate about 1 l/min) was injected to the circulation flow to fully mix with the air pumping from the clothing microclimate. Normally, C_{amb} was less than 1%, then the resulted C_{in} was around 11%.

Body movement and wind

To investigate the influence of movement of the body and the surrounding air, the manikin was set into two states: standing still and walking at a speed of 45 ± 1 double steps/min. A wind tunnel was used to create the forward wind and the wind speed was set as no wind (< 0.2 m/s, chamber air movement only), 0.4 m/s and 2.0 m/s respectively.

RESULTS

Fig. 1 shows the ventilation V , the heat transfer coefficients h_t , and the evaporative heat transfer coefficients h_e for three jackets measured when the manikin was standing or walking in three wind conditions of no wind (< 0.2 m/s), in wind of 0.4 m/s and 2.0 m/s respectively.

Microenvironment ventilation (V)

Fig. 1 (a) and (b) show the total ventilation under three jackets in six experimental conditions. When there is no wind and the manikin stands still, the ventilation is the lowest of all the tests for the three jackets because only air penetration through the fabric and natural convection takes place. Since the three jackets are of same style, there should be little difference in natural convection through openings. The ventilation of jackets PVC and MEM are almost the same and lower than 10 l/min., indicating that the material of jacket MEM is almost air impermeable and the natural convection for these jackets is very low. The higher ventilation of jackets TEX is due to the good air permeability of the normal textile material. When the wind speed is as low as 0.4 m/s, the ventilation shows a small increase only from the respective

no-wind conditions for all three jackets, indicating that low wind has only a limited effect on ventilation. When the wind speed is as high as 2.0 m/s, the ventilation increases greatly for all jackets.

When the manikin is walking in no wind, the ventilation (compared to static) increases for all the jackets because of the pumping effect. However, the increment of jacket TEX is much higher than the other two jackets which are air impermeable. This must be due to air penetration through the textile material increasing with the increased air pressure under jacket TEX due to the pumping effect. In wind of 0.4 m/s, the ventilation is similar to the respective one in no wind, indicating an interaction of two effects of pumping and wind. When the wind gets high as 2.0 m/s, the ventilation increase due to walking is less than that when the wind speed is low, again due to the presence of an interaction of pumping and wind effects. This confirms the findings by Havenith and Nilsson: when the walking effect was studied in relation to wind, it was evident that the larger the wind, the smaller the walking effect.⁽²²⁾

Heat transfer coefficient (h_t)

As shown in Fig. 1 (c) and (d), the heat transfer coefficient h_t (the inverse of the thermal insulation I_t) increases as the wind speed increases and movement is present as body walking, showing similar patterns to the ventilation change. However, the difference between air permeable and impermeable jackets is not as much as that of ventilation, indicating that the ventilation difference due to air permeability doesn't have a big influence on dry heat loss. The dry heat transfer coefficient h_t is composed of a convective part h_c and a radiative part h_r : $h_t = h_c + h_r$. Standing in no wind, radiation is the main way for heat loss. The heat transfer coefficient of naked body h_r is 4.5 (W/m²K),⁽²³⁾ for the two layers case in this study, the radiative heat transfer coefficient of clothing should be $\frac{1}{2}h_r$.⁽⁸⁾ The values of h_t for all three

fabrics standing in no wind are around $2.25 \text{ (W/m}^2\text{K)}$, indicating that the convective heat loss was very low. Taking out h_r as a parallel resistance by using the calculation method proposed by Havenith et al.,⁽⁸⁾ the values of h_c at static no wind conditions for all three fabrics are as low as around $0.7 \text{ (W/m}^2\text{K)}$.

The measured ventilation V consists of penetration and convection, the big ventilation difference between permeable jacket TEX and impermeable jackets PVC and MEM is due to air penetration. The close values for the heat transfer coefficients of the three jackets indicate that the penetration effect on heat transfer is small. As convection increases with walking and wind for all jackets, heat transfer increases as well.

Evaporative heat transfer coefficient (h_e)

Fig. 1 (e) and (f) show the evaporative heat transfer coefficient h_e (the inverse of the vapor resistance R_e). It increases as the wind speed increases and body walking is present, showing a similar pattern to the ventilation change while the difference among jackets are much bigger.

When the manikin stands still in no wind, although the ventilation of jacket MEM is almost the same as jacket PVC due to its poor air permeability, its evaporative heat transfer coefficient is as high as jacket TEX which is air and vapor permeable. This difference of h_e between jackets PVC and MEM must be caused by the high (static) vapor permeability of jacket MEM's material which is close to the static value for the normal textile material of jacket TEX. Because of the special way of vapor transfer of the membrane coated material, the used trace gas argon does not transfer through this material as vapor. It is confirmed that such vapor diffusion which is separated from air movement through fabric has not been measured as ventilation by using the trace gas method.

However, as the ventilation increases with wind, the difference of moisture transfer between jackets TEX and MEM becomes bigger. For normal polyester fabric which is not very tightly woven, its air and vapor penetration through the material is closely related. The forced convection due to wind causes an increase in air change through fabric TEX already at the lower air speed, and simultaneously the moisture transfer through the fabric also increases. But it is not the case for jacket MEM since it is almost air impermeable as jacket PVC. Here only the highest wind and the pumping have impact.

When the manikin walks in no wind, the evaporative heat transfer coefficient h_e for jackets TEX is obviously higher than that for jacket MEM due to the increased air penetration through fabric caused by pumping effect. In Fig. 1 (f), the difference among jackets is due to the vapor permeability of fabrics. The three polylines which are almost parallel to each other (i.e. no interaction effect of walking with textile type) indicate that the vapor permeability of fabrics doesn't change much with wind conditions when walking.

Dry versus evaporative heat transfer

Fig. 2 shows heat transfer coefficient (h_t) versus evaporative heat transfer coefficient (h_e) for three jackets, changing with conditions. In the reference condition (standing in no wind), the jacket TEX is close to the jacket MEM, both are far to the right of the PVC jacket. This indicates that the air permeability makes no big difference of dry and evaporative heat loss of jackets in the condition without any forced convection while the fabric vapor permeability plays a big role in evaporative heat loss. Once wind is added, air movement through the jacket increases vapor transfer through jacket TEX greatly while no such effect in jacket MEM. From that point, the two jackets begin to be separated far in the h_t - h_e plot.

For jacket TEX, four h_t - h_e dots in four forced ventilation conditions locate almost in a line, and the values of $\Delta h_t/\Delta h_e$ between two windy conditions are almost the same. It confirms that in condition with forced convection, the dry heat loss is coupled with the evaporative heat loss in air and vapor permeable textile materials. For jacket MEM, the value of $\Delta h_t/\Delta h_e$ between two windy conditions while walking is higher than that while standing, and the h_e value for walking is slightly lower than that for standing in 2 m/s wind. This indicates that the pumping effect has some interaction with wind on vapor transfer. For jacket PVC, the value of $\Delta h_t/\Delta h_e$ between two windy conditions while walking is close to that while standing, confirming that the vapor transfer is only through air movement in air and vapor impermeable materials.

DISCUSSION

For all three jackets, V , h_t and h_e increases with forced convection caused by walking or wind, which is consistent with the findings by Havenith et al..^(2,8) However, comparing the slopes of the lines in Fig. 1(a), (c) and (e) with the respective ones in Fig. 1(b), (d) and (f), it is clear the increment rates with low and high winds in walking condition are obviously lower than the respective ones in standing condition with only a few exceptions. This indicates the interaction of wind and pump effect on ventilation, dry and evaporative heat transfer.

If ignoring the effect of the radiative heat transfer, the patterns of h_t for the jackets MEM and PVC look very similar with the respective ones of V . This reveals that the convection through openings is the only way for dry heat transfer except for radiation for air impermeable jackets. The close values of h_t of jackets TEX and PVC confirm that the different air permeability of materials doesn't reflect a big influence on dry heat loss. In the study of correction of clothing insulation for movement and wind effects, Havenith and Nilsson⁽²²⁾ also found that no significant nor graphically visible effect of air permeability was present by

re-analysis of the Havenith et al. ^(2,8) and Holmér et al. ⁽²⁴⁾ data (standing still). However, the outdoor jackets are usually required to be wind-protective to a certain degree and thus the textile materials for jackets are usually tightly woven and their air permeability are relatively lower. It is also the case for the work clothing used in the above mentioned study which needs to be durable and are often tightly woven. For the TEX material, although the air penetration through the material is measured as ventilation, it is too ineffective to form air flow which is helpful for dry heat transfer. Therefore, the air permeability of materials doesn't make big difference on thermal resistance in this paper. However, the effect of high air permeability on dry heat transfer needs to be further investigated in future.

As mentioned above, the different vapor permeability of three materials separate three jackets in the vapor resistance plots shown in Fig. 1 (e) and (f). For jackets TEX and PVC, the data for wind show a high similarity for the response of ventilation and of vapor resistance. When looking at walking however, there is a discrepancy between the ventilation and the vapor resistance effect for all three fabrics. This suggests that the pumping effect that walking causes has a different impact on the ventilation measurement and the vapor resistance measurement. It seems that the ventilation measurement overestimates the effect on vapor resistance. Possibly this is a more complex issue of how air is exchanged between different compartments in the jackets, that affects both measurements differently.

As a waterproof and breathable material, jacket MEM has a thin, porous fluoropolymer membrane coating that is bonded to the fabric. This membrane is impermeable to liquid water but allows the water vapor molecules to pass through. However, it is almost as air impermeable as the material of jacket PVC but is as vapor penetrable as the normal fabric of jacket TEX in static conditions. Although the molecular size of argon which is used as trace gas is close to that

of water molecule, the way for them to penetrate through the membrane seems different. The small difference of ventilation V between jackets PVC and MEM confirms that the argon gas cannot penetrate through jacket MEM. The big difference of h_e between two jackets confirms that for such special material, the vapor resistance cannot be predicted from the ventilation V measured by the trace gas method using argon. Havenith et al. mentioned earlier that the trace gas method could be applied in the absence of layers with water molecule specific transport mechanisms such as the hydrophilic layers in some semipermeable materials. ^(8,11)

The moisture permeability index i_m provides a relationship between evaporative and dry heat resistance of clothing.

$$i_m = 1000 \times I / (L \times R_e) = 1000 \times h_e / (L \times (h_c + h_r)) \quad (\text{dimensionless}) \quad (5)$$

Fig. 3 shows the i_m values for the three jackets, for the different conditions. In Eq. (5), L denotes Lewis constant (16.7 °C/kPa), h_e and h_c increase similarly due to walking and wind whereas h_r remained unchanged. Therefore i_m , using this definition, increases when convection increases. ^(8,11) Under the reference condition, i_m for jackets TEX and MEM are 0.47 and 0.42, which is higher than that of most garments with values close to 0.38 reported by McCullough et al.; ⁽²⁰⁾ for jacket PVC made of air impermeable material, i_m is much lower at 0.14, as to be expected. For jacket TEX, where h_e and h_c contain the effect of penetration through the fabric, the i_m values are greater than the respective ones for the air and vapor impenetrable jacket PVC. However, i_m shows similar increase pattern for two jackets. The i_m change of jacket MEM shows a different pattern, fluctuating around 0.4. For jacket MEM, as shown in Eq. (2), h_e contains two parts, one part is due to convection which increases similarly to h_c , and the other part is caused by vapor diffusion through the material which is almost constant, similar to h_r in the convection equation thus i_m doesn't increase as much with condition change.

Three typical materials for outdoor jackets (air and vapour permeable, air and vapor impermeable, and air impermeable but vapour permeable) were studied. Since these material properties relevant to air and vapour transport were typical, the actual data were not tested. For future study materials with different levels of air and vapor permeability can be further investigated. In this study, however, the focus was on the whole ventilation, and its effect on the total thermal insulation and vapor resistance. As discussed earlier, for the condition of walking in the wind, the results showed the ventilation measurement overestimates the effect on vapor resistance, this might be associated with the fact that air exchange between different compartments in the jackets affects both measurements differently. Recently, Ke et al reported that local ventilation at right arm, chest and back varied and the difference changed with wind, garment size and fabric permeability.⁽²⁵⁾ They found that the head-on wind decreased the chest microclimate volume and as the result, it decreased the local ventilation at chest. Although the jackets used in this study are identical in design, the material stiffness is different from each other, thus different air gap distribution can be developed between manikin and the jackets. When the manikin is walking and/or wind is present, the variation of air gap distribution becomes more complicated. In future study, in addition to the permeability, the properties of I and Re from jacket materials need to be measured by using the sweating hotplate, and even measured with various spacer between the fabric and the hotplate. The material stiffness also needs to be tested. To further look at the local ventilation V , and link them with the local I and Re of jackets will deepen our understanding of the interaction of clothing ventilation with dry and evaporative heat transfer.

CONCLUSIONS

In this paper, to investigate the effect of material properties on clothing ventilation, and on heat and vapor transfer, the clothing ventilation, thermal insulation and vapor resistance of three jackets made of different materials, worn on an articulated thermal manikin, were measured under various conditions. Similar to published results, ventilation increased when movement started and/or wind was added, and the thermal insulation and vapor resistance decreased inversely to ventilation. It was found that the clothing ventilation increased with the air permeability of materials, though it did not have much influence on thermal insulation while it had a big influence on vapor resistance. As expected, ventilation measurement in the semipermeable material did not represent the full change in vapor resistance due to the membrane not being penetrable for the tracer gas used, though in the other conditions ventilation and vapor permeation were strongly linked. This relation was different in walking versus wind however, suggesting that the ventilation measurement principle differs from the vapor transfer. The effects of ventilation on heat and vapor diffusion varied because of different ways of ventilation arising, penetration through fabric was proved to be the most effective way in vapor diffusion although it seemed not very helpful for heat diffusion. It is suggested that for work clothing, especially protective clothing, to improve vapor permeability of the material is an effective way to release heat stress.

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(a) V , standing

(b) V , walking

(c) h_t , standing

(d) h_t , walking

(e) h_e , standing

(f) h_e , walking

FIGURE 1. Ventilation (V), heat transfer coefficient (h_t) and evaporative transfer coefficients (h_e) of three jackets under various conditions

FIGURE 2. Heat transfer coefficient (h_t) versus evaporative heat transfer coefficient (h_e)

(a) Standing

(b) Walking

FIGURE 3. Change of moisture permeability index (i_m) with ventilation condition