EFFECTS OF VENTILATION ON ENSEMBLE THERMAL PROPERTIES

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INTRODUCTION

It is known that physical activity affects the thermal properties of an ensemble by reducing the external air layer thickness and by developing an internal forced convection, both increasing the convection heat and mass transfer. The importance of these mechanisms has led to a more frequent use of e.g. walking manikins. Data from this type of measurement describe well the impact of the clothing on the dry heat transfer. Also the evaporative heat transfer can be sufficiently well quantified when the major routes for the evaporative and the dry heat transfer are similar. But if the ensemble is ventilated and the material layers are less permeable to water vapour then a non-sweating walking manikin may not give a relevant description of the evaporative heat loss. The reason is that the vapour transfer through the openings relative to that through the material layers can be significant different from the corresponding transfer of heat. The purpose of this paper was to discuss in general terms the effect of ventilation on the thermal conditions in clothing air layers and illustrate the importance of ventilation to the mass transfer in two very different types of chemical warfare ensembles.

MATERIALS and METHODS

For a forced air flow between e.g. two garment layers the convective heat flow rate from one layer to the *air* (fluid), Φ, can be expressed as

$$\Phi = \alpha \cdot A \cdot (T_s - T_f)$$

where α is the convective heat transfer coefficient (cf. h_c), A is the surface area and T_s and T_f are the surface and *air* (fluid) temperatures. T_f can be calculated from

$$T_f=[\alpha_s \cdot T_s \cdot A_s+\alpha_{cl} \cdot T_{cl} \cdot A_{cl}+V \cdot c_p \cdot \rho \cdot T_a]/[\alpha_s \cdot A_s+\alpha_{cl} \cdot A_{cl}+V \cdot c_p \cdot \rho]$$

where α_s and α_{cl} (not necessarily the same) are the convective heat transfer coefficients at e.g. the skin and the nearest clothing surface, A_s and A_{cl} are the skin and the clothing surface areas, V is the ventilation rate, T_a is the surrounding air temperature. The clothing vapour concentration and the mass transfer can be expressed analogously (the effect of e.g. water leakage on the insulation value of an immersion suit can also be estimated). If the clothing is tight-fitting and the apertures are closed then $T_f \approx (T_s+T_{cl})/2$. But as such conditions are rare, it can be assumed that $T_f \neq T_m$ where T_m is the mean value of the temperatures of the two opposite surfaces. Consequently the convection coefficient, h_c, commonly defined from the temperature and the heat flux at the inner surface and the temperature at the opposite surface, will not correctly describe the convective heat and mass transfer from one layer to another. Generally if $T_f > T_a$, then $h_c / \alpha_s > 0,5$ and the magnitude of the ratio will depend on the fit and ventilation rate. The internal convection coefficient and air-layer temperature were measured on one subject walking on a treadmill in **calm** air wearing a combat uniform (jacket and trousers) with the apertures open at the ankle, waist, wrist and neck. The air temperature was around **14** °C. The influence of ventilation on the evaporative heat transfer was studied on five subjects by comparing a permeable, fully closed NBC-suit with an impermeable 2-piece CW-liquid protective suit worn over a combat uniform. The dry heat transfer was measured with heat flux discs and thermocouples and the mass transfer was measured with rh-sensors and continuous whole-body weighing during walking on a treadmill at a speed of 0,8 m/s. The metabolic rate was about 600W and the climate was **22°C,** 30%rh.

RESULTS

Table **1.** The regional and the whole-body air layer temperatures, T_f **[°C],** compared with the corresponding mean temperatures, T_m [°C] when wearing the combat uniform (jacket and trousers) with open apertures. The walking velocities were **0,9,** **1,4** and **1,9 m/s.**

Part of the body	0,9 m/s T_m	0,9 m/s T_f	1,4 m/s T_m	1,4 m/s T_f	1,9 m/s T_m	1,9 m/s T_f
leg	27,6	26,1	27,4	26,2	27,8	26,4
trunk	28,1	26,0	28,0	26,2	28,1	26,1
arm	25,7	25,7	25,6	26,0	25,4	25,8
Average	27,5	25,9	27,3	26,1	27,5	26,1

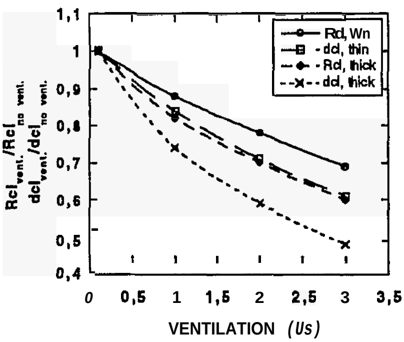
The table shows that the fluid temperature, T_f, differed considerably from T_m. The difference, about **1,4** "C for the whole body or **15%** of (T_s-T_{cl}), represents the combined effect of air exchange and surface enlargement. The difference between T_f and T_m was greater at the trunk than at the leg. This was probably because of a greater ventilation of the jacket than the trousers, an effect partly due to differences in the aperture area **(1).** At the arm, the relation between T_f and T_m was reversed compared with the other parts. The reason is that, especially at the upper arm, the air is exchanged with that coming from the warmer trunk region, not with the cooler ambient air, hence $T_f > T_m$. This re-distribution of air can be of importance for the thermal properties of an ensemble. Deviations between T_f and T_m influence the h_c/α ratio. Table **2** shows the results at the various parts of the body when the combat uniform is worn.

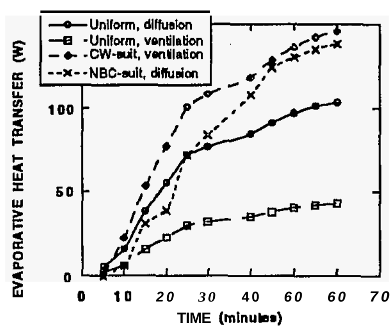
Table 2. Regional and whole-body h_c-values compared with the corresponding α-values [W/(m^{2}K)]. The walking speeds were 0,9, 1,4 and 1,9 m/s. The combat uniform (jacket and trousers) was worn with the apertures open.

Part of the body	0,9 m/s h_c	0,9 m/s α	1,4 m/s h_c	1,4 m/s α	1,9 m/s h_c	1,9 m/s α
leg	9,0	13,7	11,0	17,4	12,4	19,0
trunk	7,9	10,2	9,8	13,0	11,4	15,1
arm	5,5	11,3	6,9	14,5	7,9	17,7
Average	7,9	11,8	9,8	15,0	11,3	17,2

The whole-body h_c/α ratios were 0,67, 0,65 and 0,66 at 0,9, 1,4 and 1,9 m/s respectively. The ratio would have been about 0,5 at no air exchange and if the clothing had been skin-tight. The expected h_c/α for the uniform is around 0,60 with no ventilation, and 0,66 for an air exchange of 2 l/s. From the change in T_f and α due to ventilation and activity rate the water vapour and heat resistance values were calculated for two ensembles (Fig 1). The skin was assumed to be completely wet with a temperature of 35°C. The ambient climate was 20°C and 50%. The figure indicates that a greater air exchange results in a greater reduction of the resistance values and that the most significant change refers to the vapour resistance. The figure also suggests that the thicker (or denser) a material is the greater relative importance the ventilation should have.

Fig. 1 (left panel). Estimated effect of ventilation rate and type of ensemble, shirt and trousers (thin), combat uniform (thick), on the change in intrinsic heat resistance, R_{cl}, and vapour resistance, d_{cl}, while walking at 0,9 m/s in calm air. The results were compared with no ventilation. Fig. 2 (right panel). The evaporative heat transfer from the fully closed, permeable NBC-suit and the impermeable CW-suit worn over a combat uniform, when walking 0,8 m/s on a treadmill in calm air.





The ventilation in a conventional, permeable NBC-suit worn in a fully protection mode is negligible. Then the water vapour is transported from the skin through the material layers to the environment by diffusion. In the CW-suit, the water vapour is transferred from the skin to outside the uniform by ventilation and diffusion. The ventilation rate is roughly 1 l/s at a walking speed of 0,9 m/s in still air when wearing ensembles similar to a uniform **(2).** So, this avenue was responsible for about 30% of the evaporative heat transfer from the skin. From the outside of the uniform, the vapour was transported to the environment entirely by ventilation as the liquid protection is impermeable. The continuous weighing, relative humidity and temperature measurements showed that the ventilation rate was 3,5 l/s. This resulted in a lower total vapour resistance value than that of the thin, permeable NBC-suit. The insulation values of the two ensembles were similar. But because of the ventilation of the CW-suit less amount of water was trapped by condensation in combat uniform than in the NBC-suit. This resulted in a more rapidly increasing evaporation rate in the CW-suit and initially, a greater dry heat transfer. Fig. **2** shows that the impermeable CW-suit was as good as or even slightly better than the thin permeable NBC-suit because of the ventilation. **As** the heat production was the same in the two ensembles the slight difference in evaporation rate and dry heat transfer was also mirrored by physiological measurements. Fig. **2** (right panel) shows that the ventilation of the combat uniform was responsible for roughly 30% of the total mass transfer. This result is rather similar to that predicted as Fig. **1** suggests that a ventilation rate of 1 l/s should reduce the vapour resistance by 25-**30%** in this type of outfit.

CONCLUSIONS

The ventilation affects the air layer temperature and vapour concentration. This effect changes the convection coefficient as it has previously been defined in clothing physics. So in models accounting for ventilation through apertures (as well as through air-permeable materials), the convection coefficient must be defined by the properties of the *air* (fluid) and those at the surfaces. The effective vapour resistance of the ensemble may be greatly overestimated if the ventilation is not considered. These effects were illustrated experimentally. We found that an impermeable CW-suit worn over a combat uniform allowing *air* exchange with the ambient air could be as good as or even slightly better than a conventional, light, permeable NBC-suit in respect of heat dissipation and physiological load. The consequence is that predictions of heat load and hence, time to heat exhaustion should become more accurate if the effects of ventilation are adequately considered.

REFERENCES

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