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The Effect of Air Permeability on the Chemical Protective Performance of NBC Suits

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Summary

The heat load imposed by air-permeable NBC-protective suits can be reduced by improving the air permeability of the suit. However increased air permeability will reduce the chemical protective performance. In this study the relation between the chemical protective performance and air permeability of NBC-clothing is evaluated. Mustard vapour challenge tests were performed on a number of NBC protective materials, to evaluate their level of protection. The penetration of mustard vapour was correlated with the dynamic adsorption capacity and the air permeability of the material. The air permeability of the material appears to be a parameter of critical importance. High air permeability of the material is conflicting with a good protective performance. A theoretical model was developed, which describes the chemical protection of air permeable protective clothing material under various conditions. Using this model the effect of airflow through the material on the breakthrough of mustard vapour was calculated and compared with the results of breakthrough experiments. The predictions of the model are in good agreement with the experimental results. The relation between air permeability and protective performance provides an insight in the costs of an adequate protection in terms of physiological load.

Introduction

The NBC-protective clothing currently in use by military forces usually is an air permeable carbon-based garment. This clothing protect the wearer by adsorbing the hazardous chemical vapours onto the carbon. The thermal load of this type of clothing is low in comparison with impermeable clothing, because of the relative good transmission of air and water vapour. The heat stress on the wearer can be nevertheless a problem, especially in hot ambient environments. A reduction of the heat load can be achieved by improving the air permeability of the fabric. However, increased air permeability will reduce the chemical protective performance. In order to achieve a good compromise between comfort and protection it is useful to understand the relationship between the chemical protective performance and the air permeability. This paper presents the results of a theoretical and experimental study about this. The experimental study deals with the evaluation of sixteen NBC-protective fabrics containing various types of carbonaceous layers. A theoretical model which describes the influence of the airflow through the material on the chemical barrier properties of the fabric is presented for one typical carbon type material.

Theoretical

In the theoretical analysis only materials of the carbon bead type have been taken into account. In this type of protective clothing the filter fabric is based on a single layer of small activated carbon spheres, adhered to a carrier fabric. When an activated carbon filter is challenged by a chemical agent vapour flow, the breakthrough curve of the effluent vapour concentration against time is typically sigmoid. Typical of carbon bead type fabrics is an initial step in the breakthrough curve; immediately after exposure a very small breakthrough concentration of vapour occurs, which is roughly constant over a certain period of time. The main aim of this work is to model the initial breakthrough of the vapour.

Initial breakthrough

Several authors have studied the breakthrough of vapour through carbon filters [1-3]. A commonly used equation, which describes the vapour concentration, C , inside the filter as a function of the axial position, z , in the filter is:

$$\varepsilon \frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial z^2} - v \frac{\partial C}{\partial z} - k_g (1 - \varepsilon) \frac{3}{r} (C - C_s) \quad (1)$$

C	local concentration (kg/m^3)
C_s	concentration of vapour, in equilibrium with the adsorbed surface concentration of vapour onto the carbon (kg/m^3)
ε	bulk porosity of the carbon particles in the filter (-)
D	diffusion coefficient vapour (m^2/s)
v	superficial velocity of the air through the clothing (m/s)
k_g	mass transfer coefficient vapour between the gas and the carbon (m/s)
t	time (s)
z	axial position in the filter (m)

In the initial stages of the breakthrough, the surface concentration of vapour on the carbon, C_s , will almost be 0, because no adsorption will have taken place yet. During the initial moments, another assumption can be made: the initial breakthrough will remain constant (experimental results second this assumption). Mathematically this means that:

$$\frac{\partial C}{\partial t} = 0 \quad (2)$$

Thus:

$$D \frac{\partial^2 C}{\partial z^2} - v \frac{\partial C}{\partial z} - k_g (1 - \varepsilon) \frac{3}{r} C = 0 \quad (3)$$

The boundary conditions of this differential equation are: the concentration, C , is equal to the challenge concentration, C_0 , at the inlet of the filter ($z=0$) and is equal to the breakthrough concentration, C_{ini} , at the end of the filter bed. In the case of carbon bead type fabrics, the filter bed thickness is only one layer of carbon particles. Thus the bed thickness is assumed to be twice the radius of the particle, $2r$. Using these boundary conditions, the differential equation can be solved. This gives for the breakthrough concentration:

$$C_{ini} = C_0 \exp \left(\frac{vr}{D} \left(1 - \sqrt{1 + 12(1 - \varepsilon) \frac{D}{rv^2} k_g} \right) \right) \quad (4)$$

The mass transfer coefficient can be calculated with the number of Sherwood, Sh :

$$Sh = \frac{2r\varepsilon k_g}{D} \quad (5)$$

This number usually is a function of the air velocity, but in laminar cases it becomes equal to 2 [4]. This is assumed to be the case. The bulk porosity of the carbon particles follows from the carbon load, L , and the density of the carbon particles, ρ_k , by assuming that one minus the porosity is occupied by the carbon:

$$(1 - \varepsilon) = \frac{L}{2r\rho_k} \quad (6)$$

Which gives:

$$C_{ini} \approx C_0 \exp \left(\frac{vr}{D} \left(1 - \sqrt{1 + \frac{6}{\left(\frac{r\rho_k}{L} - 1 \right) \left(\frac{D}{rv} \right)^2}} \right) \right) \quad (7)$$

This equation describes the initial breakthrough concentration of a vapour through a NBC-protective fabric with a carbon bead filter as a function of the air velocity through the material.

50 % breakthrough

The sigmoid breakthrough curve of the effluent vapour against time can be approximated by a block shaped curve, which changes at the time where 50% breakthrough occurs. Thus, the amount of vapour, which is adsorbed on the carbon, is equal to the dose at which the carbon material was exposed, $C_0 t_{50}$, times the velocity of the vapour through the material. Taking into account the carbon load gives equation:

$$q = \frac{C_0 t_{50} v \rho_k}{L} \quad (8)$$

q	adsorption capacity of carbon for vapour with concentration C_0 (kg/m ³)
C_0	challenge concentration of vapour (kg/m ³)
t_{50}	50% breakthrough time (s)
v	superficial velocity of the air through the clothing (m/s)
ρ_k	density of the carbon spheres (kg/m ³)
L	carbon load (kg/m ²)

or

$$t_{50} = \frac{Lq}{C_0 v \rho_k} \quad (9)$$

The adsorption isotherm is known as a function of the concentration, thus q is known. A Dubinin-Radushkevich isotherm is assumed [1-3]:

$$q = q_{\max} \exp \left(\left(\frac{RT}{\beta E_0} \right)^2 \ln^2 \left(\frac{C}{C_{\text{sat}}} \right) \right) \quad (10)$$

$q_{\max}$	maximum adsorption capacity of carbon for vapour (kg/m ³)
R	gas constant (J/mol K)
T	temperature (K)
β	affinity coefficient (-)
E_0	activation energy (J/mol)
C_{sat}	saturation concentration of vapour (kg/m ³)

Air permeability

The air permeability of the fabric together with the wind speed determines the air velocity through the clothing material. For the calculation of the flow rate the following empirical equation was used (5-6):

$$v = 0.559 \Gamma v_{\text{wind}}^2 \quad (11)$$

v	superficial velocity of the air through the clothing (m/s)
Γ	air permeability of clothing material (m/Pa s)
v_{wind}	air velocity of the wind (m/s)

Experimental

The experimental study was concerned with the evaluation of a broad range of air permeable carbon-based NBC-protective fabrics. The charcoal adsorbent was present in different forms: discrete carbon beads onto a textile fabric, carbon fibres and carbon powder incorporated into a nonwoven material or foam. The fabrics were evaluated on the following properties: air permeability, mustard vapour penetration and dynamic adsorption capacity for mustard vapour.

The air resistance of the fabrics was determined by measuring the pressure difference over a material sample, while blowing air through the material with a linear velocity of 1 or 5 cm/s. The air permeability was calculated as the reciprocal value of the air resistance.

The protective performance of the fabric samples was determined using a mustard vapour challenge test. A nitrogen stream with mustard vapour was drawn through the material samples. The concentration profile of the penetrated agent was measured using a gas chromatograph with a flame ionisation detector as a detection system and the penetrated dose was calculated. The flow rate through the material simulates the flow rate under actual field situation at a wind speed of 5 m/s and is the result of the wind speed and the air permeability of the material (equation 11). The vapour challenge concentration was 11 mg/m³. The influence of the gas velocity through the material on the penetration of mustard vapour was determined for a carbon bead type fabric. The breakthrough of mustard was measured for gas velocities in the range of 0 – 8 cm/s.

The dynamic adsorption capacity of the materials was determined using a constant flow rate of 2 cm/s through the materials. The challenge concentration of mustard vapour was 230 mg/m³. From the breakthrough curve the dynamic adsorption capacity of the materials was calculated as the difference between the challenge amount of mustard and the penetrated amount of mustard.

Results and discussion

Typical results of the fabric properties are presented in Figure 1. The protection levels afforded by the fabrics are given as penetrated dosage of mustard vapour after 6-hours challenge. From these results it appears that the air permeability is an important parameter on the breakthrough of mustard vapour. Generally, fabrics with a high air permeability offer a low protection. This is also the case if their dynamic adsorption capacity is relatively high. This is because an increase of the air permeability results in an increase of the air velocity through the fabric resulting both in a less effective mass transfer process of the vapour to the carbon and an increase of the mustard vapour challenge stream through the fabric. Figure 2 shows the penetrated dose of mustard vapour as a function of the quotient of air permeability and dynamic adsorption capacity of the fabrics. Because it can be expected that the mass transfer process of the vapour to the carbon depends on the type of the carbonaceous material, the fabrics were combined in two groups, the carbon bead materials and the other materials. It appears that linear regression results in a good fit for both groups of fabrics.

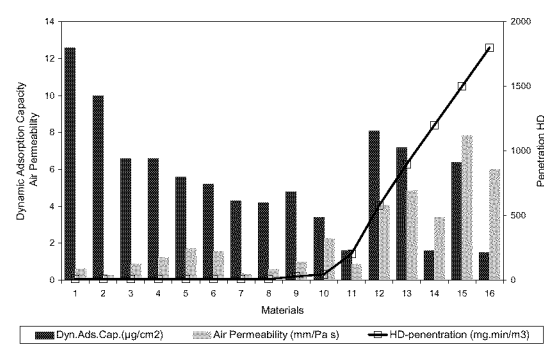


Figure 1: Fabric properties: dynamic adsorption capacity, air permeability, mustard vapour penetration.

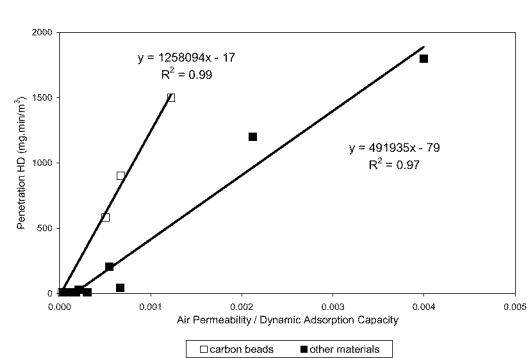


Figure 2: Correlation of the mustard vapour penetration with the ratio of air permeability and dynamic adsorption capacity.

Using the model, the influence of wind velocity and air permeability on the initial breakthrough and on the 50% breakthrough were calculated for the carbon bead type fabric. In both cases, all other important parameter values were kept constant. This values are shown in Table 1.

Table 1 Values of parameters, used in the model study.

$C_0 =$	11	mg/m^3	$\Gamma =$	0.002	$\text{m}/(\text{Pa s})$
$C_{\text{sat}} =$	910	mg/m^3	$v_{\text{wind}} =$	5	m/s
$D =$	$5.70 \cdot 10^{-6}$	m^2/s	$T =$	298	K
$q_{\text{max}} =$	609	kg/m^3	$r =$	$2.50 \cdot 10^{-4}$	m
$E_0 =$	$2.48 \cdot 10^4$	J/mol	$L =$	0.177	kg/m^2
$\beta =$	1.55	-	$\rho_k =$	$1.01 \cdot 10^3$	kg/m^3
$R =$	8.31	J/molK			

If the wind velocity and the air permeability of the clothing changes, Figure 3 and Figure 4 are found. The air velocity through the clothing depends on both the air permeability of the clothing and on the velocity of the wind. In Figure 5 the actual effect of changing the air velocity through the clothing on the initial breakthrough is shown. The curve in this figure represents the results of the model and the points are the experimental values. The time at which 50% breakthrough occurs is also dependent on the air velocity through the clothing. This effect is shown in Figure 6. The predictions of the model are in good agreement with the experimental results.

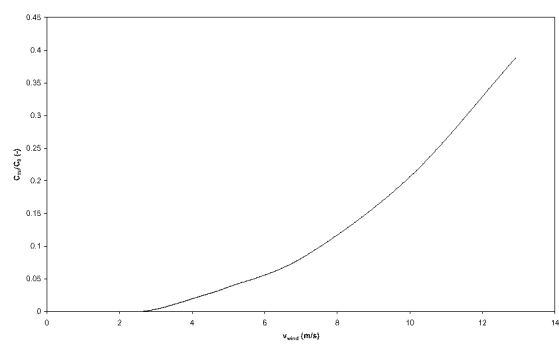


Figure 3: The effect of the velocity of the wind on the initial breakthrough.

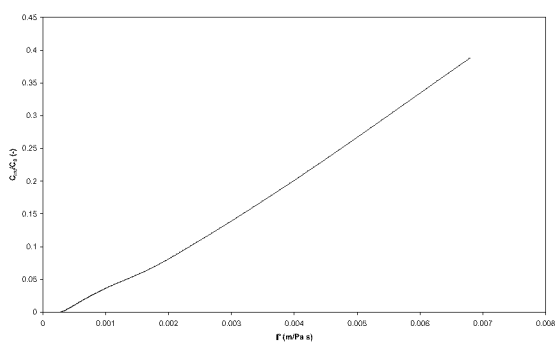


Figure 4: The effect of the air permeability of the clothing on the initial breakthrough.

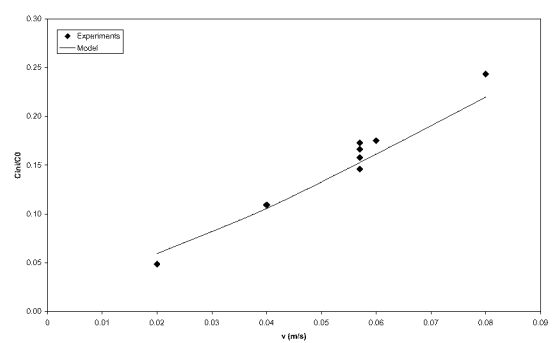


Figure 5: The effect of the air velocity through the clothing on the initial breakthrough (the curve represents the model, the points are experimental data).

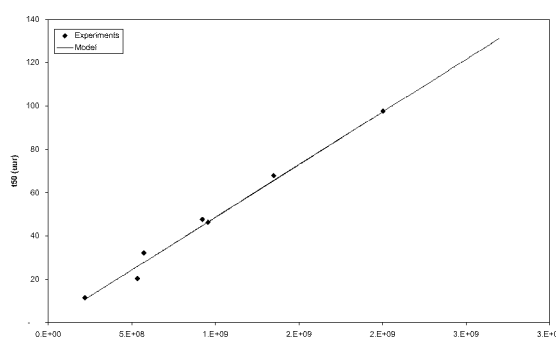


Figure 6: The effect of the air velocity through the clothing on the 50% breakthrough time (the curve represents the model, the points are experimental data).

The air velocity through the clothing results in an almost linear change in the initial breakthrough. The initial breakthrough is also almost linearly dependent on the air permeability of the clothing, which was to be expected because the air velocity through the clothing is linearly dependent on the permeability of the clothing. The wind speed has a parabolic effect on the initial breakthrough. All these effects seem quite obvious. A higher air velocity will result in less contact time between the air and the carbon, and therefore will result in a higher initial breakthrough concentration.

The 50% breakthrough time is inversely proportional to the velocity of the air through the clothing. If the air velocity is higher, more air will flow through the clothing during a certain time period. Thus more vapour must be adsorbed onto the carbon. This means that the carbon will reach its maximum adsorption capacity earlier, resulting in a decrease of the 50% breakthrough time.

Conclusions

Experimentally and theoretically, the effect of air permeability and wind speed on the chemical protective performance of NBC-protective fabrics has been studied. Higher air permeability and wind speed will result in a reduction of the protective performance of the fabrics. Therefore, the potentialities for reducing the heat load by means of improving the air permeability are limited. The proposed model for estimating the protective performance under various conditions can be used as a tool to seek for a good compromise between comfort and adequate protection.

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