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A new dynamic clothing model.
Part 2: Parameters of the underclothing microclimate

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Abstract — Based on a new modeling, described in the first part of this paper, which takes into account the pumping effect under garments, the various parameters characterising the confined air, and managing its dry and latent losses, are determined. The mean temperature, calculated from heat exchanges with skin (or underwear) and with the garment, progresses exponentially as a function of the trapped time, until a limit. The mean humidity amount, determined from the energy of total evaporation, from the air layer renewal rate and from the water vapour diffusion through the fabric, increases linearly. Using a movable thermal manikin, walking at various speeds, and with a combined effect with wind, the intrinsic air speed and convection coefficient are defined. The intrinsic air speed combines the effects of external air and body motions. The intrinsic convection coefficient is a linear function of the square root of the inner air speed. The relations expressing the trapped time are obtained, for thin and thick garments, by comparison between this new dynamic model and the model built by Lotens and Havenith (1991) which predicts the effect of posture, motion and wind on the clothing insulation. The evaluation of the amount of heat and mass transferred by pumping effect requires the knowledge of all these parameters. © 2000 Éditions scientifiques et médicales Elsevier SAS

clothing / confined air layer / pumping effect / heat and mass transfers

Résumé — Nouveau modèle dynamique de vêtement. Partie 2 : Paramètres relatifs au microclimat sous-vestimentaire. Basé sur une modélisation décrite dans la première partie de ce document, qui tient compte de l'effet de pompage sous-vestimentaire, les différents paramètres caractérisant l'air confiné, et gérant ses pertes sèches et humides, sont déterminés : la température moyenne, calculée à partir des échanges de chaleur avec la peau (ou le sous vêtement) et le vêtement, évolue exponentiellement en fonction du temps de confinement jusqu'à une limite. La teneur moyenne en humidité, déterminée à partir de l'énergie totale d'évaporation, de la vitesse de renouvellement de la couche d'air et de la diffusion de la vapeur d'eau à travers le tissu, augmente linéairement. Utilisant un mannequin chauffé et articulé, marchant à diverses vitesses, et pour un effet combiné avec le vent, la vitesse de l'air et le coefficient de convection intrinsèques sont définis. La vitesse de l'air intrinsèque combine les effets du mouvement de l'air extérieur ainsi que les mouvements du corps. Le coefficient de convection intrinsèque est une fonction linéaire de la racine carrée de la vitesse de l'air interne. Les expressions du temps de confinement pour des vêtements fins ou épais sont obtenues par comparaison du nouveau modèle dynamique avec le modèle utilisant les formules trouvées par Lotens et Havenith (1991), prévoyant les effets de la posture, du mouvement et du vent sur l'isolation vestimentaire. L'évaluation de la quantité de chaleur et de masse transférée par l'effet de pompage nécessite la connaissance de tous ces paramètres. © 2000 Éditions scientifiques et médicales Elsevier SAS

vêtement / air confiné / effet soufflet / transferts de chaleur et de masse

Nomenclature

A	numerical coefficient (in units according to the relation and the index)	
Act	activity level (1 Met $= 58.15$ W·m^{-2})	Met
B	coefficient	W·m^{-2}·K^{-1}
c	specific heat of the air	J·m^{-3}·K^{-1}
d	air density	kg·m^{-3}
D	coefficient	W·m$^{-2.5}$·K^{-1}·s$^{-0.5}$
e	thickness of garment (index cl) or of air layer	m
$Ereq$	required evaporation	W·m^{-2}
f_{cl}	area factor	
hc	convection heat transfer coefficient	W·m^{-2}·K^{-1}
hr	radiative heat transfer coefficient	W·m^{-2}·K^{-1}
H	losses from skin	W·m^{-2}
HR	relative hygrometry	%
I	insulation	m^2·K·W^{-1}
J	latent heat of water	J·kg^{-1}
P	partial pressure of water vapor in the air	Pa
R_{V}	water vapour resistance of a garment	m^2·Pa·W^{-1}
t	time	s

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T	skin or underwear surface temperature	K
T^0	mean weighted temperature	K
v	wind speed	$\mathrm{m{\cdot}s^{-1}}$
w	water vapor amount for 1 kg of dry air	$\mathrm{kg{\cdot}s^{-1}}$
x	numerical coefficients	
X	variable	

Greek symbols

α	numerical coefficient	
β	numerical coefficient	$\mathrm{m{\cdot}s^{-1}{\cdot}Met^{-1}}$
$\Theta, \overline{\Theta}$	air layer temperature, and mean value	K
τ	air renewal rate	$\mathrm{s^{-1}}$

Indices

$0, 1, 2, n$	serial number
air	relative to the ambient air
cl	relative to the fabric
dry	relative to dry heat losses
env	relative to the environment
in	relative to the inner clothing
sk	relative to the skin
v	relative to the water vapour
wind	relative to the external air velocity
Θ	relative to the confined air

1. INTRODUCTION

Many studies have been carried out to evaluate the effects of the human physical activity and of the wind on the clothing insulation, mainly:

- Gagge et al. [1], Belding et al. [2], Nishi et al. [3], Olesen et al. [4], and Vogt et al. [5] investigated the effects of movements;
- wind effects were studied by Belding et al. [2], Burton and Edholm [6];
- Crockford [7], McCullough et al. [8] presented fit and design effects;
- combined effects of movements and wind were described by Nielsen et al. [9], Havenith et al. [10], Lotens and Havenith [11].

It is well known that the variations of insulation are consequent upon air motions: permeodynamically using the porosity of the garment, and parietodynamically through apertures (collar, buttoning holes, wrists, base of trousers or dress). The model considers that the air penetrates at ambient temperature and humidity, is trapped under the garment where it is heated and charged with water vapour from secretions of the skin. Then, it is renewed at a rate linked to the confined air layer width, body movements, air permeability and suppleness of the fabric. When leaving, it drags heat and water vapour to the environment. This dynamic function, together with the resistive effect of the material, makes clothing a very effective means of keeping man comfortable in most situations.

The purpose of this study is the determination of the confined air layer parameters. They are necessary for the evaluation of heat and mass transfers through clothing. The temperature and humidity of the air layer are obtained from theoretical considerations based on dry and latent exchanges with skin and garment. Regression equations, established by Lotens and Havenith [11], resulting from combinations of posture and body movements with wind, lead to corrections of the clothing insulation, in real situations; they are here used for the determination of the air layer renewal rate. Elsewhere, the inner air velocity and heat transfer coefficient are defined from experiments in a climatic chamber, using a movable thermal manikin.

2. AIR LAYER TEMPERATURE AND HUMIDITY

2.1. Air layer temperature

Body movements and wind generate variations of the confined air thickness, by bringing and removing the garment with regard to the body. Consequently, a part of the trapped air is thrown away, and some ambient air aspirated. The air layer is the centre of convective movements, even in standing position, due to the temperature gradients between skin (or underwear) and fabric. Smithsonian tables [12], Cain and Farnworth [13] found that for a fairly typical temperature gradient of 5 K, the effective width of the trapped air is restricted to a value near to 13 mm, since wider gaps tend to show natural convection.

Let c be the specific heat of the air (1 315 $\mathrm{J{\cdot}m^{-3}{\cdot}K^{-1}}$), f_{cl} the area factor, and e the air layer thickness, these two last obtained from the difference between the clothed and the nude body areas. Energy conservation principle, applied to the confined air, leads to equation (1):

$$hc_{\mathrm{in}}\left[(T-\Theta)+f_{\mathrm{cl}}(T_{\mathrm{cl,in}}-\Theta)\right]\mathrm{d}t = ec\,\mathrm{d}\Theta \qquad (1)$$

where Θ is the air layer temperature at instant t, hc_{in} the convection heat transfer coefficient either between skin (or underwear) and air layer or between inner clothing surface and air layer, T and $T_{\mathrm{cl,in}}$ skin (or underwear) and inner clothing surface temperatures.

Let T^0 be the mean weighted temperature for the convective heat exchanges with the air layer [14]:

$$T^0 = \frac{T + f_{\mathrm{cl}} T_{\mathrm{cl,in}}}{1 + f_{\mathrm{cl}}} \tag{2}$$

This change of variable in equation (1) leads to

$$\frac{-hc_{\mathrm{in}}(1 + f_{\mathrm{cl}})}{ec}\,\mathrm{d}t = \frac{\mathrm{d}\Theta}{\Theta - T^0} \tag{3}$$

By integration the air layer temperature at any instant t is obtained:

$$\Theta = T^0 - \left(T^0 - T_{\mathrm{air}}\right)\exp\left(-hc_{\mathrm{in}}\frac{1 + f_{\mathrm{cl}}}{ec}t\right) \tag{4}$$

T_{air} is the ambient temperature. τ being the air renewal rate (times$\cdot$s^{-1}), the mean value of the air layer temperature, during the time of confinement $t = 1/\tau$ is

$$\overline{\Theta} = \tau \int_0^{1/\tau} \Theta\,\mathrm{d}t$$

$$\overline{\Theta} = T^0 - \frac{(T^0 - T_{\mathrm{air}})ec\tau}{hc_{\mathrm{in}}(1 + f_{\mathrm{cl}})} \cdot \left(1 - \exp\left(-hc_{\mathrm{in}}\frac{1 + f_{\mathrm{cl}}}{ec\tau}\right)\right) \tag{5}$$

2.2. Air layer humidity

Skin perspiration and sweating is supposed to be evaporated at the skin level, and evacuated both by diffusion through fabric and by air renewals.

If *Ereq* is the required evaporation (W$\cdot$m^{-2}), i.e. the necessary energy to get by water evaporation a null thermal balance, J the latent heat of water ($2.45\cdot10^6$ J$\cdot$kg^{-1}), d the air density (1.3 kg$\cdot$m^{-3}), each kg of dry air is augmented every second by the amount of water w_1 (rate per second):

$$w_1 = \frac{Ereq}{Jde} \tag{6}$$

The amount of water vapour evacuated by diffusion decreases the water content of the air layer by w_2 (rate per second):

$$w_2 = \frac{P_\Theta - P_{\mathrm{air}}}{Jde_{\mathrm{cl}}R_{\mathrm{v}}} \tag{7}$$

R_{V} (m$^2\cdot$Pa$\cdot$W^{-1}) is the water vapour resistance of the garment, which takes here into account its outer and inner boundary air layers, and e_{cl} the thickness of the garment; P_{air} and P_Θ are, respectively, the partial pressures of the ambient air and of the air layer.

Convective movements are supposed to make uniform the air layer state with respect to the temperature and humidity. The mean humid state is obtained by numerical integration: the stay time of the air layer is subdivided in steps of 1/5 second. At first time, the temperature and water amount of the air layer (Θ_0, x_0) are equal to those of the ambient air $(T_{\mathrm{air}}, x_{\mathrm{air}})$. Let w_n be the mean value of the water vapour amount of the air gap during the stay time t and N the total number of steps. The air layer temperature at each step is given by the following equation:

$$\Theta_n = T_{\mathrm{air}} + \frac{2n(\overline{\Theta} - T_{\mathrm{air}})}{N}$$

For n varying from 1 to N, the water vapour amount w_n of the air gap increases by $(w_1 - w_2)/5$ with regard to the last step (w_1 and w_2 are calculated at each step). So:

$$w = \frac{\sum_n w_n}{N} \tag{8}$$

However, this method corresponds to parietodynamical air renewals. In the case of permeodynamical movements, the air, for a part, is heated and humidified when crossing the garment. For this case, a more sophisticated method has to be built.

When the pumping action leads to a contact between a wet skin and the garment, a part of humidity is transferred to the fabric by capillary action. In this case the skin wetness is decreased, and the fabric is cooled. If the sweat evaporation at skin level is the only efficient way to cool the body, the perception of comfort is nevertheless increased by the decreasing wetness. The humidity pumped directly by the garment is here considered null (sweating not leading to formation of droplets, but being only a moistness); its evaluation is complex, depending on the nature of the textile, and leading to difficulties in the determination of the clothing temperature and humidity (sorption effects etc.).

3. INTRINSIC WIND SPEED AND CONVECTION COEFFICIENT

The movements of the air under clothing correspond to an inner wind. Its velocity is a parameter difficult to be measured. It depends on the measuring site and on the air gap width. Moreover, air permeability, suppleness of the garment, and body movements play an important role on the intrinsic air speed value.

The intrinsic convection coefficient is linked to the inner wind speed. Hence, both parameters are evaluated in the same time, by the same experiments here described.

3.1. Method

Measurements were performed in a climatic chamber, using a clothed heated manikin. They are detailed hereafter. The method is to evaluate the effects of the movements of the manikin and of the outside wind on the clothing insulation I_{cl}, and consequently, on the intrinsic heat transfer coefficient h_{cl}, where

$$\frac{1}{I_{\mathrm{cl}}} = h_{\mathrm{cl}}$$

The heat transfer is the sum of a radiative heat transfer and of a convective heat transfer. The former is made of two, respectively, between skin and garment and between skin and environment (through clothing), but both independent of the air layer width and velocity, and only functions of skin, garment and radiative ambient temperatures, transmission of clothing, and emission coefficients of the surfaces. The latter is the intrinsic convection heat transfer, depending on the body movements and on the air gap width.

The relation between the air velocity and the convection coefficient under clothing is of the same nature as for the outer surface of the whole body, when walking in still air or in wind [15]:

$$hc_{\mathrm{in}} = D v_{\mathrm{in}}^{x} + B$$

v_{in} is the intrinsic wind speed. It has the same relation as the effective wind speed at the outer surface, composed of two terms; the first accounts for the effect of wind and the second for the body exercise:

$$v_{\mathrm{in}} = \alpha v_{\mathrm{wind}} + \beta(Act - 1)$$

v_{wind} is the external air velocity ($\mathrm{m{\cdot}s^{-1}}$), *Act* the activity level expressed in Met (the Met is a common unit to evaluate the metabolic rate according to the activity: 1 Met is for a seated person when relaxing; 1 Met is equal to 58.15 $\mathrm{W{\cdot}m^{-2}}$). The coefficients D, B, α, β, and the power x are determined from experiments and by using a regression method.

The intrinsic clothing insulation I_{cl} of the clothing ensemble is defined by the difference between mean skin temperature and surface clothing temperature (inside equal to outside for thin garments), and the dry heat loss rate from skin H_{dry}:

$$I_{\mathrm{cl}} = \frac{T_{\mathrm{sk}} - T_{\mathrm{cl}}}{H_{\mathrm{dry}}}$$

3.2. Experimental methods

The articulated manikin belongs to the French Textile Institute, fitted with 35 individually controlled thermistors, and owns a surface of 1.67 $\mathrm{m^2}$. The ensemble used is composed of trousers, shirt, socks, and shoes, corresponding to a reference insulation of 0.52 clo. The skin temperature was set at 34 °C, and the mean radiant temperature of the chamber was equal to the air temperature (22 °C). The relative humidity, was controlled at 34 % in all sessions.

Standing position ($Act = 1.2$ Met), and two walking speeds (0.26 $\mathrm{m{\cdot}s^{-1}}$, i.e. $Act = 1.5$ Met; and 0.56 $\mathrm{m{\cdot}s^{-1}}$, i.e. $Act = 2.0$ Met) were tested for each of these four wind conditions: no wind (i.e. $v_{\mathrm{wind}} < 0.12\ \mathrm{m{\cdot}s^{-1}}$); 0.3 $\mathrm{m{\cdot}s^{-1}}$; 0.6 $\mathrm{m{\cdot}s^{-1}}$; 1.45 $\mathrm{m{\cdot}s^{-1}}$. The manikin always faced the wind.

3.3. Results

From the manikin measurements (*table I*), and with a regression method, the different parameters were fixed

TABLE I
Heat transfer coefficients for all experimental situations.

Act	v_{wind} ($\mathrm{m{\cdot}s^{-1}}$)	h_{cl} ($\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$)
Standing	0	12.4
	0.30	11.7
	0.60	12.9
	1.00	14.6
	1.45	16.5
Walking at 0.26 $\mathrm{m{\cdot}s^{-1}}$	0	17.4
	0.30	15.4
	0.60	15.7
	1.00	16.9
	1.45	17.9
Walking at 0.56 $\mathrm{m{\cdot}s^{-1}}$	0	15.7
	0.30	16.5
	0.60	16.9
	1.00	20.8
	1.45	22.2

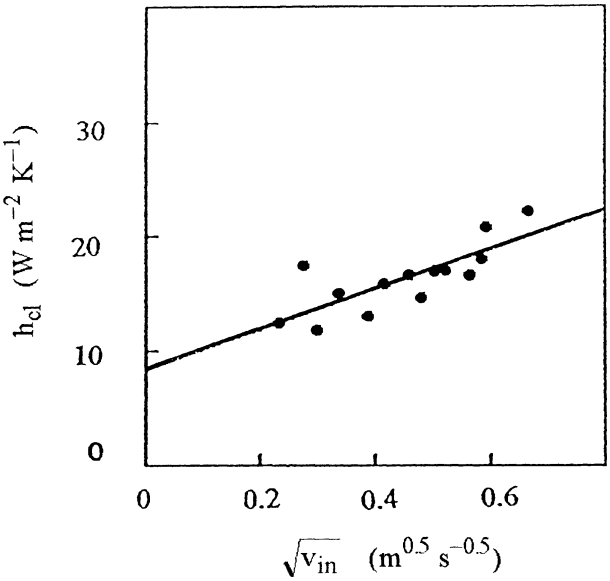


Figure 1. Variation of the heat transfer coefficient with the square root of the intrinsic air speed.

to give the best possible results (*figure 1*). Equations (9) and (10) give, respectively, the intrinsic heat transfer coefficient and wind speed:

$$h_{cl} = 8 + 17.5\sqrt{v_{in}} \tag{9}$$

$$v_{in} = 0.20v_{wind} + 0.15(Act - 1) \tag{10}$$

The number 8 is a coefficient with the same unit as B, 17.5 another one with the same unit as D, 0.15 with the same unit as β.

4. AIR RENEWAL RATE

Backward and forward motions of clothing relatively to body, during exercise and in windy environment create a pumping effect. The air penetrates through pores and apertures, stays some time under the garment, then is evacuated and replaced by another volume of the ambient air. Evaluating the amount of heat and mass transfer by air renewals requires the knowledge of the renewal rate. When the level of activity increases, the trapped time becomes shorter, leading to increased convective and mass losses. These last are necessary to evacuate the excess of body heat and mass production.

4.1. Method

The static model of Gagge et al., which supposes heat and mass exchanges only at clothing surface, is transformed in a dynamic model by using regression equations given by Lotens and Havenith [11], expressing the insulation variations with wind and walking speed, and validated using a data bank, consisting of a number of studies reported in the literature. It is called “Present Model” (PM). The model studied here, which takes into account the pumping effect, is called “New Model” (NM).

PM and NM are computed in Turbo Pascal 6.0. The programs run with input data, related to the environmental parameters (air temperature T_{air} and relative humidity rh; radiant temperature T_{rad}; air velocity v_{wind}), to clothing properties (radiative emission and transmission ε_{cl}, τ_{cl}; thickness e_{cl}; reference insulation $I_{cl,ref}$; and garment vapour resistance R_v), and to body characteristics (size; weight; and activity level *Act*).

The total heat exchanges are evaluated with PM, using the program for combination of activities and wind speed. For identical input data, and with NM, the trapped time $t = 1/\tau$ of the air layer is sought, to give the same variations in total heat losses as do the variations of clothing insulation in PM. That way, the trapped time variations with wind and exercise are obtained by NM, according to the insulation variations predicted by Lotens and Havenith.

4.2. Calculation

The NM was subdivided into two, according to the fabric thickness. This consideration was taken to keep simple expressions, and thus, non-numerous parameters to adjust. Indeed, the thickness of a fabric is linked to its suppleness and air permeability, and, consequently, affects the micro-climate. So, for an average person, six ensembles were studied: three for the thin NM (0.5 clo; 0.6 clo; 0.7 clo); and three for the thick NM (0.84 clo; 1.0 clo; 1.2 clo).

Each ensemble was tested for the standing position and three walking speeds, corresponding to the activity levels: 1.2 Met, 1.4 Met; 2.0 Met; 2.9 Met. Each activity is carried out in five environments, differing only by their wind speed conditions: no wind; 0.3 m·s^{-1}; 0.7 m·s^{-1}; 1.4 m·s^{-1}; and 4.1 m·s^{-1}.

PM does not take into account the vapour resistance of the garment nor its radiative transmission, but all other input data are the same as in NM (*table II*).

TABLE II

Input data for NM (0 for very small values of e_{cl}).

	I_{cl} (clo)	R_{v} ($\text{m}^2 \cdot \text{Pa} \cdot \text{W}^{-1}$)	e_{cl} (mm)	ε_{cl}	τ_{cl}	T_{air} (°C)	T_{rad} (°C)	HR (%)
Thin garments	0.50	2	0	0.60	0.30	24	24	50
	0.60	2	0	0.60	0.30	24	24	50
	0.70	2	0	0.50	0.30	24	24	50
Thick garments	0.84	2	1.00	0.50	0.20	18	18	50
	1.00	2	1.85	0.50	0.15	16	16	50
	1.20	2	2.50	0.50	0.12	14	14	50

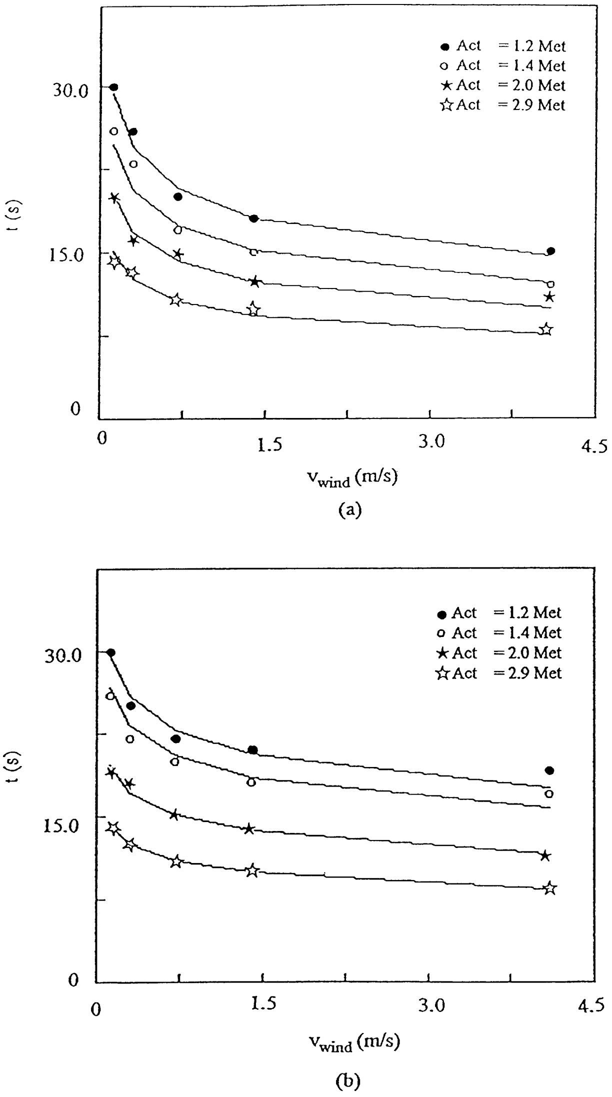


Figure 2. Variation of the trapped time with activity and wind for thin (a) and thick (b) garments.

TABLE III

Variation of the coefficient $A = t v_{\text{wind}}^{x}$ (t: time of confinement, v_{wind}: outside air velocity, x: coefficient) with exercise and insulation.

	$I_{\text{cl,ref}}$ (clo)					
	Thin ensembles			Thick ensembles		
Act (Met)	0.50	0.60	0.70	0.84	1.00	1.20
1.2	5.55	11.08	19.23	12.86	21.77	40.99
1.4	5.52	10.05	16.32	11.90	19.45	33.27
2.0	5.38	8.71	13.21	9.99	14.29	21.08
2.9	4.40	6.97	9.43	8.55	10.41	13.37

The aspect of the trapped time variation with wind speed provides the relation (*figures 2(a)* and *(b)*):

$$t = \frac{A}{v_{\text{wind}}^{x}}$$

Least squares fix the coefficient A and the power x. For thin garments $x = 0.2$, and for thick garments $x = 0.15$. The coefficient A varies with exercise and reference insulation (*table III*). For each activity, the coefficient A, depending on the insulation, is a linear relation (*figures 3(a)* and *(b)*), with

$$A = \frac{A_0}{Act^n}(I_{\text{cl,ref}} - I_{\text{cl,0}}) + A_1$$

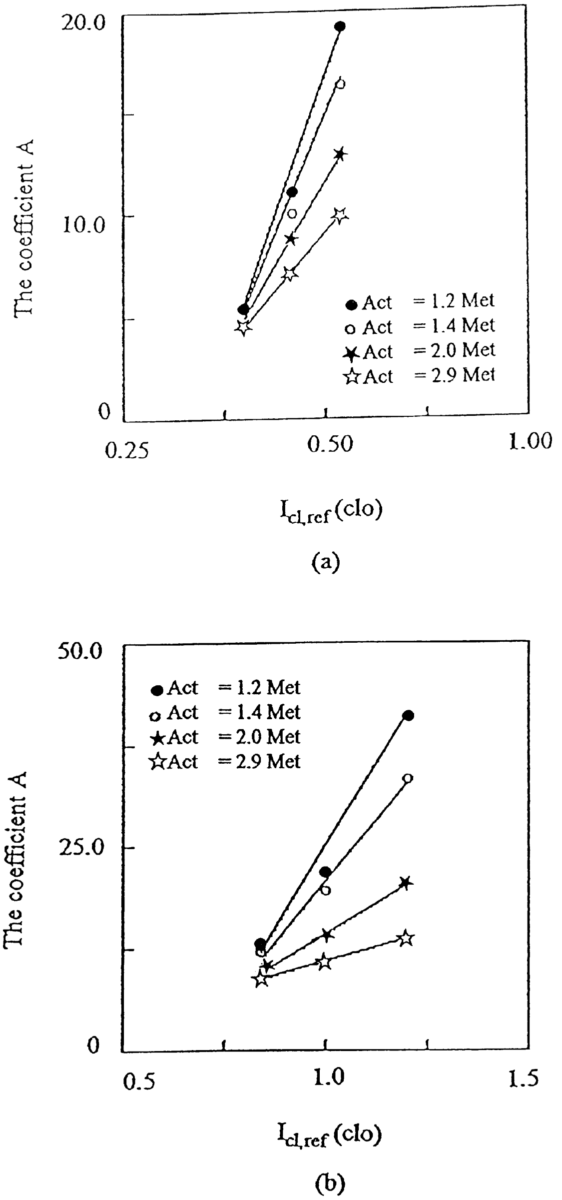
The coefficients A_0, A_1, $I_{\text{cl,0}}$, and the power n are obtained by least squares. Their units are linked to those of present variables (and the same for the numbers 79, 4, 8 in the following relations). So, the trapped time, function of exercise and wind speed, is given by relations (11) for thin ensembles and (12) for thick ensembles:

$$t = \frac{(79/Act)(I_{\text{cl,ref}} - 0.47) + 4}{v_{\text{wind}}^{0.2}} \tag{11}$$

$$t = \frac{(119/Act)(I_{\mathrm{cl,ref}} - 0.80) + 8}{v_{\mathrm{wind}}^{0.15}} \qquad (12)$$

The validity domain of expressions (11) and (12) is restricted to

wind speed 0–5 $\mathrm{m{\cdot}s^{-1}}$
walking speed 0–1.5 $\mathrm{m{\cdot}s^{-1}}$
reference insulation $>$0.47 clo for equation (11) and $>$0.80 clo for equation (12)



$I_{\mathrm{cl,ref}}$ (clo)

(a)

$I_{\mathrm{cl,ref}}$ (clo)

(b)

Figure 3. Variation of the coefficient A with intrinsic insulation and activity for thin (a) and thick (b) ensembles.

5. DISCUSSION

5.1. Trapped air temperature and humidity

The relative motion between skin and fabric is an active system to manage latent and dry losses. The air layer confined between skin and fabric constitutes a microclimate owning properties different from the ambient air properties. In a rough approximation, its temperature (equation (5)) increases exponentially as a function of time until reaching a maximum which corresponds to a mean value weighted between skin and air temperatures, but its water vapour amount (equation (8)) increases linearly (until saturation if the air renewal rate is too low). *Figure 4* shows that the trapped air is heated during its confinement before it is charged with water vapour. This characteristic is interesting with regard to the comfort sensation, because, if the renewal rate is sufficient, the air layer removes from saturation when heated, and so, allows the confined air to charge more evaporation from skin secretions. In fact, this is the technique for clothing and colonial dwelling in warm humid climate: ventilation and a small heating. The comfort feeling is much more the result of the possibility of evaporating than of the equilibrium of the thermal balance.

5.2. Intrinsic wind speed and convection coefficient

Relations (9) and (10) expressing the intrinsic wind speed and the convection coefficient represent a first approach of mean values. Complementary experiments have to be carried out to reach more accurate relations,

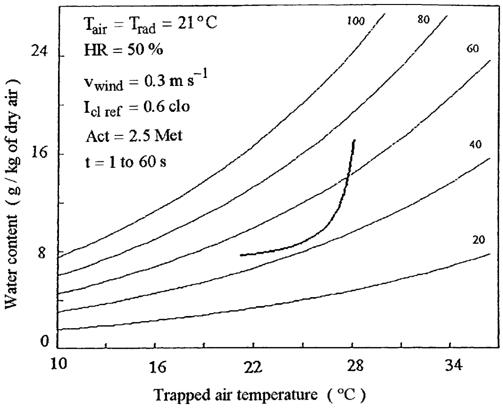


Figure 4. Variation of the air gap temperature and water vapor amount during a trapped time of 60 s represented on a psychrometric diagram.

but this first determination was necessary in the new modelling, and so, in evaluating the amount of heat and mass losses by pumping effect.

The intrinsic air velocity is less than the outer effective air velocity, the effect of body motion on the wind speed being nearly the same either on the inner or outer sides of clothing; but the inner air velocity is 80 % smaller for a thin ensemble, and 85 % for a thick garment, with regard to the external net air velocity. Thus, clothing constitutes a barrier against wind.

The inner convection coefficient hc_{in} seems as large as the outer one (maybe larger), since the temperature gradient and the air motion are significant for such a narrow space. In the literature, there is a few investigations of this parameter, one being presented by Danielsson [15]: by heat flux sensors measurements for a loose fitting one layer ensemble (combat uniform), he found an intrinsic convection coefficient of

$$hc_{\text{in}} = 14.5 v_{\text{in}}^{0.34}$$

The number 14.5 is a mathematical coefficient of which the unit is obviously linked to those of the present variables: $\text{W}\cdot\text{m}^{-2.34}\cdot\text{K}^{-1}\cdot\text{s}^{-0.34}$.

The constant term 8 in the expression of h_{cl} contains the constant term in the expression of hc_{in} and the radiative transfer coefficients between skin and both clothing and environment. The subdivision requires complementary experiments not carried out until now. The high values of hc_{in} given by Danielsson or by the present determination confirm an underclothing convection certainly more important than generally considered. The kind of clothes (wide or adjusted, supple or stiff, with collar and wrist openings etc.) also intervenes. Here again, complementary experiments must be carried out.

5.3. Air layer renewal rate

Equations (11) and (12) show a lower effect of wind in the case of a thick garment than for a thin one. In the first case, indeed, the apertures are less numerous, the fabric is generally not supple and weakly permeable. In *figure 5* are presented the trapped times predicted by formulas (11) and (12) with comparison to the calculated values with NM: they lead to the same variations of total heat losses as do the variations of clothing insulation provided by Lotens and Havenith [11]. The accuracy is comparable to their results.

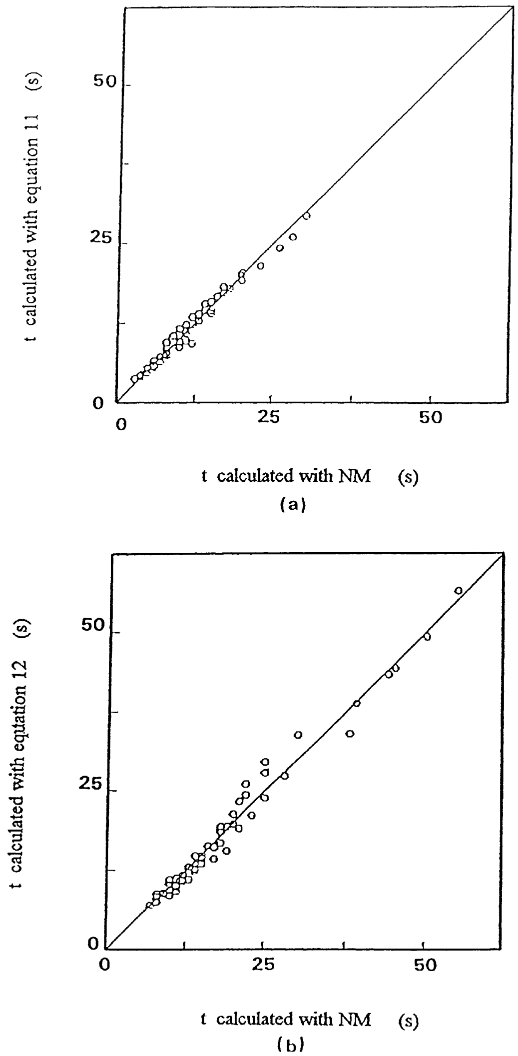


Figure 5. Correlation between calculated trapped time by NM and by using the regression equations on activity and wind for thin (a) and thick (b) garments.

At a greater renewal rate the effect of dry and latent exchanges become more significant with the increase in intrinsic wind speed. There are also a number of other changes in the inner environment: the convective and evaporative coefficients rise, the air layer temperature draws near to the ambient temperature.

Conversely, when the renewal rate is low, the temperature and humidity of the confined air increase, and consequently, the partial pressure of water rises. Provided the garment is water vapour permeable, the diffusion rate through the garment increases.

The contribution of the underclothing air layer in improving a comfort sensation has been used since ages. In a hot and dry climate, the mean problem is the dryness of an air withering and chapping the skin at 20 % relative humidity. Clothes are thus covering to keep the air layer a long time near skin by restricting its renewal. Its humidity increases in consequence of sweat evaporation. Convective exchanges are negligible and the comfort sensation is consequent from the air humidity near skin. Moreover, the air gap can be cooler when the ambient air temperature is above the mean skin temperature. Lower air temperatures are met in warm and humid climate than in dry climate; the air layer is warmer than the ambient air, and its relative humidity is less. Consequently, it can contain more water vapour. To avoid saturation, the air gap must be renewed frequently, because evaporating is the comfort condition, and the air, even warmed, can collect a small amount of water vapour. Clothes are thus loose and opened. Berger et al. [16] demonstrated that in near-saturated air conditions, people prefer a higher temperature to a higher relative humidity because their adaptation to temperature is faster. Air renewals are desirable in cold climate when the body is sweating. A wet clothing, indeed, will cause afterchill; however, the renewed air layer has to be situated between two fabric layers, to avoid a cold air at skin contact which could cause bronchitis or anything else. The underwear then acts as a passive resistance. In the other cases, the air gap becomes an insulation, and the diffusion process of water vapour through garment remains the main way to eject the humidity from skin to the atmosphere.

6. CONCLUSIONS

Equations (5) and (8) give the temperature and water vapour amount expressions concerning the air layer. They represent mean values for the time of confinement. The air layer is heated before it is charged with water vapour proceeding from skin secretion. This characteristic helps the body evaporating.

The intrinsic wind speed is the sum of two terms: a function of wind and a function of body motion.

The convection coefficient in the air gap is a linear relation of the square root of the intrinsic wind speed.

Equations (11) and (12) predict the change of confined time with wind and activity in agreement with results of Lotens and Havenith [11] for clothing insulation.

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REFERENCES

[1] Gagge A.P., Burton A.C., Bazett H.C., A particle system of units for the description of heat exchanges in man with his thermal environment, Science 94 (1941) 428–430.

[2] Belding H.S., Russel H.D., Darling R.C., Folk G.E., Analysis of factors concerned in maintaining energy balance for dressed men in extreme cold: effects of activity on the protective value and comfort of an Arctic uniform, American Journal of Physiology 149 (1947) 223–239.

[3] Nishi Y., Gonzalez R.P., Gagge A.P., Direct measurement of clothing heat transfer properties during sensible and insensible heat exchange with thermal environment. ASHRAE Trans. 81 (1975) 183–199.

[4] Olesen B.W., Sliwinska E., Madsen T.L., Fanger P.O., Effect of body posture and activity on the thermal insulation of clothing: measurements by a movable thermal manikin, ASHRAE Trans. 88 (1982) 791–805.

[5] Vogt J.J., Meyer J.P, Candas V., Libert J.P., Sagot J.C., Pumping effect on thermal insulation of clothing worn by human subjects, Ergonomics 26 (1983) 963–974.

[6] Burton A.C., Edholm O.G., Man in a Cold Environment, Edward Arnold, London, 1955.

[7] Crockford G.W., Trawlers fishermen's protective clothing, in: Wiener J.S., Maule H.G. (Eds.), Human Factors in Work, Design and Production: Case Studies in Ergonomic Practice, Vol. 1, Taylor & Francis, London, 1977, pp. 65–100.

[8] McCullough E.A., Jones B.W., Huck P.E.J., A comprehensive data base for estimating clothing insulation, ASHRAE Trans. 91 (1985) 29–47.

[9] Nielsen R., Olesen B.W., Fanger P.O., Effect of physical activity and air velocity on the thermal insulation of clothing, Ergonomics 28 (1985) 1617–1632.

[10] Havenith G., Heus R., Lotens W.A., Resultant clothing insulation: a function of body movements, posture, wind, clothing fit and ensemble thickness, Ergonomics 33 (1990) 67–84.

[11] Lotens W.A., Havenith G., Calculation of clothing insulation and vapour resistance, Ergonomics 34 (1991) 233–254.

[12] Smithsonian Physical Tables, Smithsonian Institute, Washington, 1934.

[13] Cain B., Farnworth B., Two new techniques for determining the thermal radiative properties of thin fabrics, Journal of Thermal Insulation 9 (1986) 301–332.

[14] Berger X., The pumping effect of clothing, International Journal of Ambient Energy 9 (1988) 37–46.

[15] Danielsson U., Convection in clothing air layers, in: Proceedings of the Fifth International Conference on Environmental Ergonomics, 1992, pp. 70–71.

[16] Berger X., Grivel F., Deval J.C., Thermal comfort in a hot climate (in French), Rexcoop report, Contract AFME-CNRS n° 4 330 2326, 1985.

[17] Sari H., L'interface vêtement—Echanges hygrothermiques et microclimat sous-vestimentaire, Thèse, Université de Nice-Sophia Antipolis, France, 1994.