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A new dynamic clothing model. Part 1: Heat and mass transfers

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Abstract — Beyond an insulating function, clothing constitutes a dynamic system managing the hygro-thermal exchanges between body and environment. The model built, presented here, and computed in the form of a user-friendly software, points out the interfacing function. The air confined under garment creates a micro-climate responsible for the felt comfort. The exchanges between the external side of clothing and the outer environment are lower than in a "static" insulating model, but are to be added to the transfers by renewal of the confined air. This model constitutes a tool giving a comprehensive valuation of the real transfers. It is useful for studies concerning thermal comfort and fabrics. © 2000 Éditions scientifiques et médicales Elsevier SAS

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

Résumé — Nouveau modèle dynamique de vêtement. Partie 1 : Transferts de masse et de chaleur. Au delà d'une fonction d'isolation, le vêtement constitue un système dynamique de gestion des échanges hygro-thermiques entre le corps humain et l'environnement. Le modèle construit, et présenté ici, a été programmé sous forme d'un logiciel convivial. Il montre le rôle interface du vêtement : un microclimat est réalisé par l'air confiné sous le tissu, qui est celui ressenti par la peau, et dont dépend l'impression de confort. Les échanges en surface externe du vêtement sont montrés être moindres que dans un modèle de type isolant "statique", mais il faut leur ajouter des échanges par renouvellement de l'air confiné. Ce logiciel constitue un outil pour l'étude du confort ou celle des tissus. © 2000 Éditions scientifiques et médicales Elsevier SAS

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

Nomenclature

Adu	surface of the body	m^2
C	convective heat losses	W
Cond	conductive heat losses	W
e	thickness	m
E, *Ereq*, *Emax*	humid transfer energy, required evaporation, maximum possible evaporation in the air	$W\cdot m^{-2}$
f_{cl}	area factor	
f_{eff}	efficiency factor	
F_1	gray form factor	
F_{pcl}	Nishi factor	
hc, *hr*	convective and radiative heat transfer coefficients	$W\cdot m^{-2}\cdot K^{-1}$
h_e	evaporative coefficient	$W\cdot m^{-2}\cdot Pa^{-1}$
I	insulation (1 clo = 0.155 $m^2\cdot K\cdot W^{-1}$)	clo
K	numerical coefficient	$W\cdot m^{-2}\cdot K^{-1}$
P	partial pressure of water vapor in the air	Pa
R	infrared losses	W
R_e, R_v	resistance to evaporation	$Pa\cdot m^2\cdot W^{-1}$
S	solar heat losses	W
T	skin, fabric or underwear surface temperature	K
V	wind speed	$m\cdot s^{-1}$
w_{req}	required wetness	

Greek symbols

α	absorptivity	
ε	emissivity	
ζ	transmittivity	
Θ, $\overline{\Theta}$	air layer temperature, and its mean value	K
κ	conductive heat transfer coefficient	$W\cdot m^{-2}\cdot K^{-1}$
λ	conductivity	$W\cdot m^{-1}\cdot K^{-1}$
ρ	reflectivity	
ϕ_e, ϕ_d	direct and diffuse solar fluxes	$W\cdot m^{-2}$
Φ	incident solar flux	$W\cdot m^{-2}$
τ	air renewal rate	s^{-1}

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Indices

0, 1, 2, 3, n	serial number
air	relative to the ambient air
cl	relative to the fabric
eff	effective
env	relative to the environment
in	relative to the inner clothing
ref	reference: standing position, still air
s	solar
sk, skin	relative to the skin
uw	relative to the external side of the underwear
v	relative to the water vapour
wind	relative to the external air velocity

1. INTRODUCTION

In the past, clothing for cold climates was essentially designed with respect to the insulating effect of the material. This often lead to bulky clothes that were not always comfortable to wear. The modern demand is for clothing that is looser and more comfortable to wear whilst providing equal levels of insulation. This is achieved using multiple layers of relatively thin materials. This approach leads to renew the air trapped between skin and fabric via a bellows action. This renewal is associated with variations of the air velocity under fabric [1, 2], of the dry and humid exchange coefficients at skin and garment levels [3, 4], and even sometimes with a wick effect to carry a part of skin wetness onto the fabric, which then behaves as a complementary evaporating area [5].

A study of the underclothing micro-climate parameters was the aim of the companion paper (part two). This first part evaluates the dry and humid transfers for a model, named “New Model” (NM), subdivided into four options by consideration of a thin or a thick fabric bounding a renewed air layer, and by the presence or not of a thick underwear at skin contact. The “static” model of Gagge [6] has been completed with the Nishi factor F_{pcl} [7], and with the expressions of the variations of the clothing insulation according to activity and wind [8]. Assuming this model, named “Present Model” (PM), giving a correct evaluation of the dry and humid exchanges, NM was adjusted to PM to get the same total losses. The interest for NM lies in a comprehensive and more realistic description of the various transfers, and to point out the importance of some parameters, such as the transparency of a fabric for radiative exchanges.

Of course, the realization of NM and the study of the micro-climate were two jobs fulfilled at the same time, different in their goals, but complementary, and this justifies our presenting them together. The complexity of the models requires a user-friendly software.

This paper is derived from the work made for a contract (ADEME-ITF 1990 n°0.04.0125), and reported in Sari’s thesis [4]. To shorten it, every detail is here not explained, more information being given in the thesis. The aim of this paper is to present a model which gives a realistic description of the underwear microclimate, useful for various applications such as studies of comfort or properties of clothes.

2. LIMITS FOR A SIMPLE MODEL

The external surface area of a garment is greater than the body’s area *Adu* by a factor f_{cl} for which the expression has been deduced by photographic measurements, and related to the reference (standing position in still air) clothing insulation $I_{cl,ref}$ (expressed in “clo” units, $1\ \text{clo} = 0.155\ \text{m}^2{\cdot}\text{K}{\cdot}\text{W}^{-1}$):

$$f_{cl} = 1 + K\,I_{cl,ref} = 1 + \frac{e}{r} \qquad (1)$$

where K depends on the clothing bulkiness, e the clothing thickness, and r the radius of the body in a cylindrical approximation (1.7 m high, $r = 0.155$ m). Twenty years ago, the average value of K was evaluated at about 0.12 [9], and is estimated today at 0.31 [10]. Considering equation (1) with $K = 0.2$, a 1 clo garment thickness is nearly 3 cm, which is that of a fabric (around 1–2 mm), and that of the confined air. The conductivity λ of this air, if it were still, should be $\lambda = e/I = 0.03/0.155 = 0.19\ \text{W}{\cdot}\text{m}^{-1}{\cdot}\text{K}^{-1}$, quite different from that of a still air layer (0.026), or that of a fabric (0.043), independent of the nature of the fabric [8, 10, 11]. So, the confined air layer does not behave as a passive insulation, but is the place of strong convective movements, justified by its vertical dominant disposition, and by the separation by a few centimeters of two surfaces (skin and internal fabric) with a dozen degrees gradient.

The humid transfer energy is usually written in the form

$$E = h_e F_{pcl}(P_{skin} - P_{air}) \qquad (2)$$

where h_e is a coefficient, proportional to the convective coefficient *hc* by the Lewis factor ($16.5{\cdot}10^{-3}\ \text{K}{\cdot}\text{Pa}^{-1}$, often considered too high and lowered to $16.0{\cdot}10^{-3}$), F_{pcl} the Nishi factor [12], corrected by Oohori et al. [13], and $P_{skin} - P_{air}$ the difference between the saturated vapour pressure at skin level and the water vapour partial pressure of the air. The quantity $h_e F_{pcl}$ behaves as the inverse of a resistance:

$$h_e F_{pcl} = \frac{1}{R_v} = 0.016hc(1 + 0.344hc\, I_{cl,ref})^{-1} \tag{3}$$

Thus,

$$R_v = (0.016hc)^{-1} + 21.5 I_{cl,ref} \tag{4}$$

The numbers $(0.016)^{-1}$ and 21.5 are coefficients expressed in Pa·K^{-1}, being derived from the Lewis factor. The first term represents the resistance of the air layer, outside clothing, the second the resistance of clothing in its thickness. When relating insulation and thickness e by the way of f_{cl} (for instance, $K = 0.2$ leads to $e = r K I_{cl,ref} = 0.155 \cdot 0.2 \cdot I_{cl,ref}$), this last term becomes:

$$21.5 I_{cl,ref} = 0.69e \tag{5}$$

From its obtention, with e expressed in mm, the number 0.69 is a coefficient expressed in Pa·m·W^{-1}. Such an evaporative resistance, as that given by equation (5), is quite different from that of a fabric (7 per mm), in many cases independent of the nature of the fabric [14], or of a still air layer (2.2 per mm) [11]. It is much weaker, which confirms the transfer in the confined air insured by a more efficient process than diffusion through a still air: a transfer by an air moving from skin (high water vapour pressure) to fabric (low water vapour pressure).

The existence of a confined air layer renewed as a function of the activity or the air agitation makes that the basic insulation is not constant. From thermal losses measured on clothed manikins and subjects, relations have been established [8], and *figure 1* illustrates an example.

In another part, from its conception, a fabric owns a porosity, and consequently a transmittivity to radiations [3, 15, 16]. A "jean", for instance, can permit 15 % of solar or IR fluxes to cross it, a pullover 25 % (*table I*) [4]!

So, the transfers are not effected in their totality at the external clothing surface level. The variable insulation, the Nishi factor, the clothing temperature on the external side do not correspond to the physical reality, but to a mathematical model fitting well with the measured thermal losses.

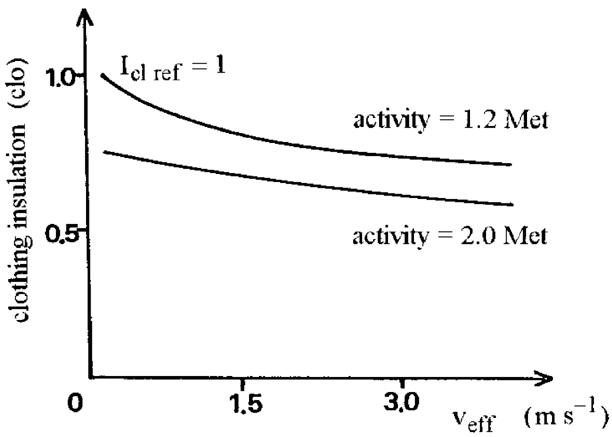


Figure 1. Variation of the intrinsic insulation with activity and wind (from data given in [8]).

TABLE I
Solar and infrared parameters for a few common fabrics. Measurements with emissometer Elan 520, and reflectometer Elan 511 [4].

Nature	Fiber	Thickness (mm)	ρ_s	α_s	ζ_s	ρ_{cl}	α_{cl}	ζ_{cl}
T-shirt	cotton	0.363	0.56	0.36	0.08	0.10	0.41	0.49
pull	cotton	0.505	0.02	0.10	0.88	0.20	0.28	0.52
pull	60 % wool 40 % acryl.	0.786	0.17	0.24	0.59	0.17	0.22	0.51
trousers	tergal	0.315	0.39	0.37	0.24	0.27	0.18	0.55
shirt	30 % polyes. 70 % cotton	0.149	0.54	0.42	0.04	0.28	0.20	0.52
"jean"	cotton	0.858	0.56	0.14	0.30	0.27	0.15	0.58
wind cheater	polyamide	1.243	0.36	0.19	0.45	0.38	0.12	0.50
jogging trousers	cotton	1.770	0.37	0.25	0.38	0.31	0.27	0.42
winter shirt	65 % polyes. 35 % cotton	0.228	0.40	0.41	0.19	0.34	0.12	0.54

3. HEAT AND MASS TRANSFERS IN NM

3.1. Generalities

NM considers the convective and evaporative respiratory exchanges as in PM. It also considers head (7 % of the body area) and hands (5 %) not covered by the garment. For these two cutaneous parts, the dry and humid exchanges are the same in the two models. It is not the aim of the present paper to discuss the expressions adopted (they can be modified if necessary), but to have in view two different decompositions of the same energies.

The two models also consider the solar flux incident on the covered human body. When adopting the cylindrical approximation, the mean flux, for any arbitrary given square meter of covered human body, has the expression

$$\Phi = \frac{\phi_e}{\pi} + \phi_d \tag{6}$$

where ϕ_e and ϕ_d are the direct and diffuse solar fluxes incident on a vertical square meter facing the azimuth of the sun.

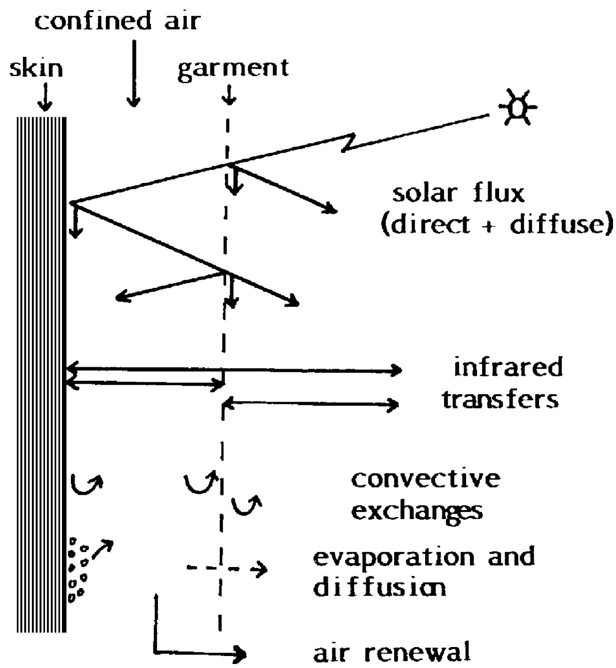


Figure 2. Schematic diagram of the hygro-thermal transfers considered in NM–thin garment.

3.2. Transfers through a thin garment confining an air layer

3.2.1. Convection

Figure 2 shows a schematic diagram of the various hygro-thermal exchanges considered with this model. The garment is assumed having no thickness, and no calorific capacity. Three surfaces are concerned by convective exchanges: skin, internal and external parts of the fabric. If T_{cl} is the fabric temperature, and Θ the confined air temperature at an instant t, then the exchanges are

$$C_1 = 0.88\, hc_{in}(\Theta - T_{sk})Adu \tag{7}$$

$$C_2 = 0.88\big(hc_{in}(\Theta - T_{cl}) + hc(T_{air} - T_{cl})\big)Adu\, f_{cl} \tag{8}$$

The coefficient 0.88 is introduced to consider the relative part of covered body. hc_{in} is the inner convective coefficient, concerning any internal side, and determined in the complementary paper (Part 2). hc deals with the external side of the fabric, and has the same expression as in PM. Convective exchanges with the confined air govern the confined air heating (equation (1) in Part 2). The mean temperature $\overline{\Theta}$ of the confined air in function of the time duration $1/\tau$ of confining (equation (5) in Part 2) shows an exponential heating until a limit situated between skin and outside temperatures.

3.2.2. Water vapour transfer

In any configuration of NM, the excreted sweat is assumed to be evaporated at the skin level, which is the optimum way for comfort. Of course, with a pearling moistness, a part of humidity can be transferred by capillary action to the underwear, if it exists, or to the external garment by contact, and then evaporated. This complex procedure of transfer is not considered here, lowering wetness, fabric temperature and thermal resistance. The comfort feeling can be improved if there is no sticking problem.

The humid secretion comes from perspiration and sweating. The water evaporated on one square meter of body increases the absolute humidity of the confined air by an amount w_1, though a quantity w_2 is transferred by diffusion through the garment (equations (6) and (7) in Part 2), and a third quantity ejected by air renewal. The resistance to water vapour transfer R_v is composed of three terms: the resistances of the two boundary air layers on each side of the fabric, and the resistance of the fabric itself. The two first have an expression [11] depending on the inner wind speed V_{in} (see Part 2), and on the effective air velocity outside the garment V_{eff} [8], the third on the fabric thickness e_{cl} [14]:

$$R_v = \frac{13.55}{\sqrt{V_{in}}} + \frac{13.55}{\sqrt{V_{eff}}} + 3\,200 e_{cl} \tag{9}$$

The numbers 13.55 and 3 200, extracted from the above references, are coefficients with the units $Pa{\cdot}m^{2.5}{\cdot}s^{-0.5}{\cdot}W^{-1}$ and $Pa{\cdot}m{\cdot}W^{-1}$ to be in accordance with the units of the variables in the relation (9).

So, in many cases, the garment behaves as a system which creates two boundary air layers, being thiner as the air velocity and the activity become greater. The fabric contribution in the total resistance is small, about a tenth, nearly independent of the nature of the textile (the diffusion process being a molecular process governed by Fick's law). It is important to notice that the association of the exponential heating, with the linear increase of water content, has the consequence of a removing the confined air away from saturation.

3.2.3. Solar radiation

The fabrics have a non-negligible transmittivity due to the empty space between yarns, and to reflections inside or between yarns and fibers. The solar flux Φ incident by square meter of clothed surface is either transmitted (transmittivity τ_s), absorbed (absorptivity α_s), or reflected (reflectivity ρ_s). *Table I* shows these parameters for a few common clothes. Some fabrics have the peculiarity of having different absorptivities for their inner and outer surfaces, but this peculiarity is not considered here. In NM two quantities have to be considered:

(1) The solar energy S_{sk} absorbed by skin (skin absorptivity 60 %). When considering the clothed (88 %) and nude (12 %) parts of body, S_{sk} has the expression:

$$S_{sk} = 0.6\, Adu\, \Phi f_{eff}\left[0.88\zeta_s(1+0.4\rho_s)+0.12\right] \quad (10)$$

f_{eff} is the efficiency factor, expressing the ratio of surface irradiating towards the outside environment. f_{eff} concerns the clothed as well as the nude parts. The term $0.4\rho_s$ considers the flux transmitted through the garment, reflected by skin and again by the garment, and finally absorbed by skin.

(2) The solar energy absorbed by the garment:

$$S_{cl} = 0.88\, Adu\, f_{cl} f_{eff} \Phi \alpha_s\left[1+0.4\tau_s(1+0.4\rho_s)\right] \quad (11)$$

3.2.4. Infrared radiation

As for textile properties in the visible range, there also exists similar ones in the infrared band (emissivity ε_{cl}, absorptivity α_{cl}, transmittivity ζ_{cl}). Three energies are concerned by infrared radiation:

(1) The radiative energy lost (negative) by skin for the benefit of the filled part of the garment:

$$R_1 = 0.88\, hr_1(T_{cl}-T_{sk})Adu(1-\zeta_{cl}) \quad (12)$$

hr_1 is the coefficient of exchange, expressed by

$$hr_1 = 4F_1\sigma\left[\frac{T_{sk}+T_{cl}}{2}+273\right]^3 \quad (13)$$

In this expression, the temperatures are expressed in Celsius degrees, σ is the Stefan–Boltzman constant, and F_1 the gray form factor between two cylinders:

$$F_1 = \frac{1}{1/\varepsilon_{sk}+(1/f_{cl})[1/\varepsilon_{cl}-1]} \quad (14)$$

ε_{sk} is the skin emissivity.

(2) The energy lost (negative) by skin towards the outer environment (mean radiant temperature T_r), through the empty part of the garment:

$$R_2 = 0.88\, hr_2(T_r-T_{sk})\zeta_{cl}\, Adu\, f_{eff} \quad (15)$$

with similar expression of hr_2 as for hr_1 ($F_2 = \varepsilon_{sk}$).

(3) The energy lost by the filled part of the garment towards the outer environment is

$$R_3 = 0.88\, hr_3(T_r-T_{cl}) f_{eff}\, Adu\, f_{cl}(1-\zeta_{cl}) \quad (16)$$

and the same for hr_3 ($F_3 = \varepsilon_{cl}$).

3.2.5. Temperature of the garment

The temperature of the garment is obtained by writing the null balance of all the energies concerning the fabric (negative when lost):

$$S_{cl} = C_2 - R_1 - R_3 \quad (17)$$

T_{cl} is present several times in the terms of equation (17). Thus it cannot be obtained easily. The way is to start from an approximate value, and to proceed by iterations.

3.2.6. Skin wetness

Instead of introducing the Nishi factor, the required wetness w_{req} is usually calculated by writing the ratio between the required evaporation *Ereq* to insure a null thermal balance of the body (thus, *Ereq* is calculated to obtain a null thermal balance computed), and the maximum possible evaporation *Emax* on the confined air for the clothed part of body, and on the external air for head and hands:

$$w_{req} = \frac{Ereq}{Emax} \quad (18)$$

with

$$Emax = 0.137\big[0.88(P_{sk} - P_\theta)\sqrt{V_{in}} + 0.12(P_{sk} - P_{air})\sqrt{V_{eff}}\,\big] \quad (19)$$

The number 0.137 is a dimensioned coefficient which is explained in detail in [1]. P_θ is the partial water vapour pressure in the confined air. All pressures are in pascals. Here, the same value of P_{sk} is adopted for the clothed and nude parts of the body. But for more precision, the code considers the water vapour pressures for the clothed part, and at head and hand levels.

3.2.7. The underclothing micro-climate

The theoretical description of NM was completed by two studies (see Part 2). The renewal rates with activity and wind were deduced, with a view to get the same dry and humid total losses as in PM, the insulation being variable with activity and wind [8]. The inner convective coefficients and the intrinsic air velocity were got from an experiment in a climatic chamber with a heated manikin.

Consequently, NM is identical to PM for the clothing behavior in terms of transferred energies. But NM gives a realistic description of the physical phenomena.

3.3. Thick garment

To consider a non-negligible fabric thickness comes to consider two thin fabric layers and a thermal resistance (in addition to the water vapour resistance still considered in the thin garment model). The garment has two temperatures T_{cl1} and T_{cl2} for its inner and outer sides. The infrared and solar radiative properties of half a fabric $(\rho_0, \zeta_0, \alpha_0)$ are obtained by geometrical considerations (as for a double glazing in building studies) from those for the whole fabric$(\rho_{cl}, \zeta_{cl}, \alpha_{cl})$:

$$\rho_0 = \frac{\rho_{cl}}{1+\zeta_{cl}} \quad (20)$$

$$\tau_0 = \tau_{cl}\sqrt{1-\left(\frac{\rho_{cl}}{1+\zeta_{cl}}\right)^2} \quad (21)$$

$$\alpha_0 = 1 - \rho_0 - \zeta_0 \quad (22)$$

The various energies taken into consideration are more numerous and complicated in their expressions, but they are obtained in the same logic way as in NM–thin garment. For instance, the solar flux absorbed by the internal part of the garment is

$$S_1 = 0.88\,Adu\, f_{eff}\, f_{cl1}\,\Phi\alpha_{cl}\zeta_{cl}\big(1+\rho_{cl}^2+0.4\zeta_{cl}\big) \quad (23)$$

The expressions are similar for the external and clothed body parts S_2 and S_k. As for the infrared transferred energies, are considered:

- the energy R_{cl12} lost by the internal side of the garment to the benefit of the external side; this transfer has the form of a conduction;
- the energy R_{cl1} lost by the internal side, through the external side, to the benefit of the outer environment;
- the energy R_{cl2} lost by the external side to the benefit of the environment;
- the energies R_{skcl1} and R_{skcl2} lost by skin to the benefits of the internal and external sides of the garment;
- the energy R_{skenv} lost by skin through the textile, to the benefit of the environment;
- the energy *Cond* transferred by conduction between the two sides of the garment:

$$Cond = 0.88\,Adu\, f_{cl1}\kappa\,(T_{cl2} - T_{cl1}) \quad (24)$$

with

$$\kappa = \frac{0.043}{e_{cl}} \quad (25)$$

e_{cl} being the fabric thickness, expressed in meter; 0.043, being a coefficient of conductivity, has the dimension of this parameter. The fabric temperatures are obtained by iterations, from the equations expressing the equilibrium between gains and losses (being present several times in the terms of the equations, a simple relation cannot be used):

$$S_1 - R_{skcl1} + R_{cl12} + R_{cl1} + Cond = 0 \quad (26)$$

$$S_2 - R_{skcl2} - R_{cl12} + R_{cl2} - Cond = 0 \quad (27)$$

The thermal balance of a clothed man is obtained from body gains and losses, and the wetness as in NM–thin garment.

3.4. Thin garment and underwear

In the same way as for NM–thick garment, the various transferred energies are expressed: the underwear is considered as a thick garment, made of two layers, one in contact with skin (so at skin temperature for the internal side), the other at T_{uw}. The external side bounds the confined air. As for the garment in PM, the underwear is a "passive" insulation crossed by thermal conduction and water vapour diffusion (no relative movement with body). The skin secretion is supposed evaporated at skin level, and then transferred into the confined air.

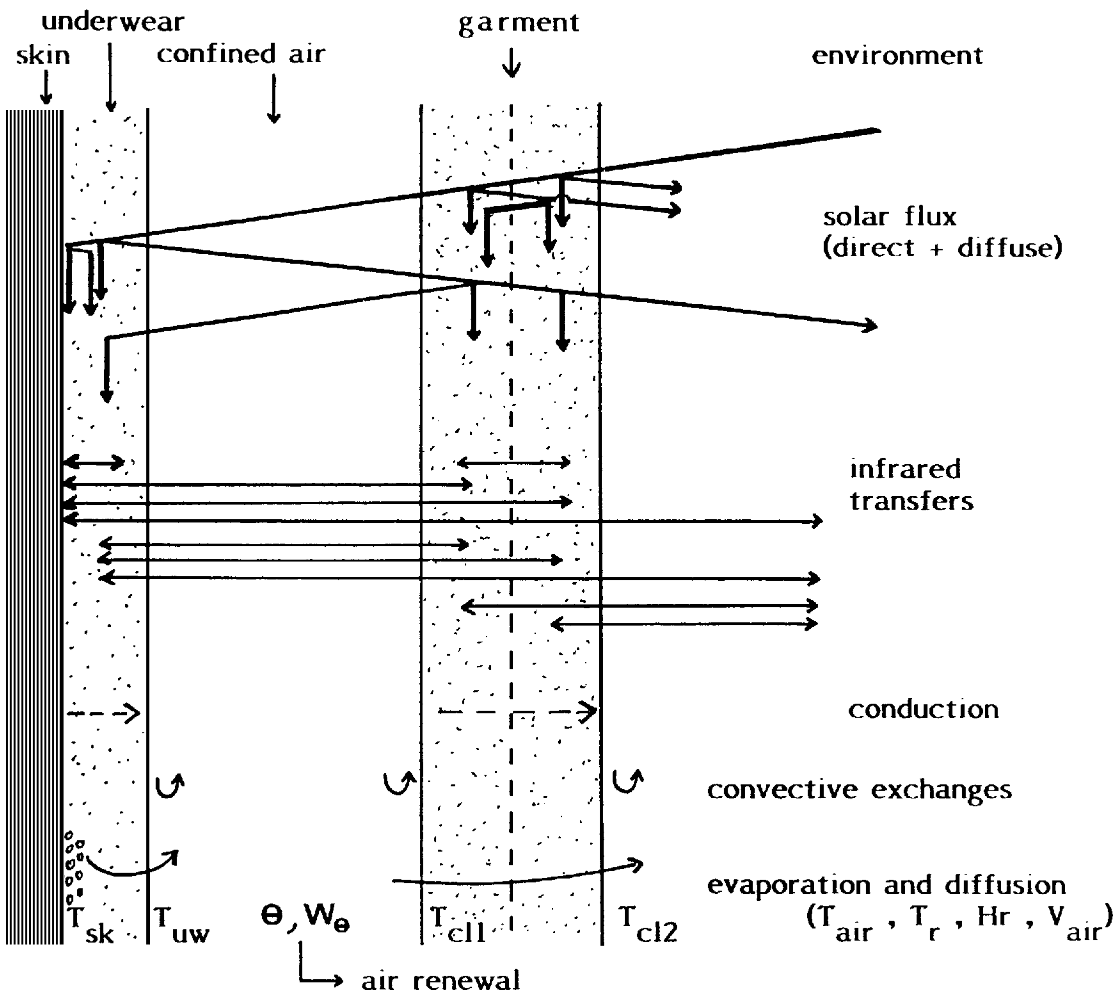


Figure 3. Schematic diagram of the hygro-thermal transfers considered in NM–thick garment + underwear.

3.5. Thick garment and underwear

The combination of cases 3.3 and 3.4 leads to numerous and complicated expressions [15] which are established in the same way as for the preceding models. Giving them is out of the objective of this paper, but *figure 3* shows them in a schematic diagram.

4. EXERCISES: "PASSIVE" AND "DYNAMIC" TRANSFERS

For an identical thickness (i.e. for an identical exchange area towards the outside environment), the three following cases of clothing in the same conditions of human activity and cold environment are considered (no solar irradiance):

- a thick winter cloth acting as passive insulation;
- a thick garment (as an acrylic wool pullover) confining an air layer between skin and garment, which is renewed;
- a moderate thick garment worn over an underwear (as a "jean" shirt and a cotton underwear). The renewed air layer is lain between the underwear and the external garment.

Figure 4 shows the results corresponding to these three cloth conceptions leading to identical dry losses:

- one third of the convective transfers is not effected at the clothing external surface level, but comes from the air renewal;

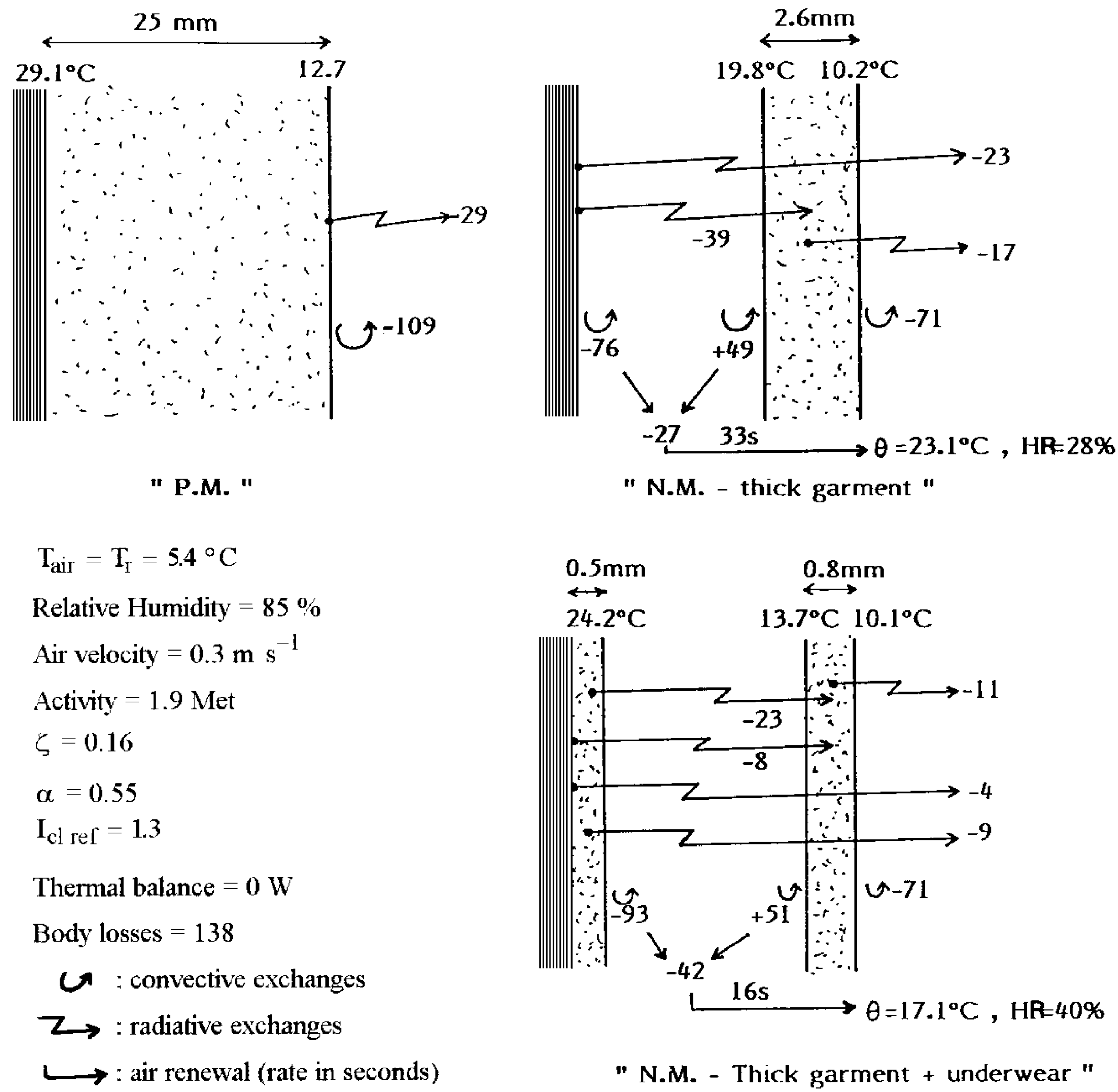
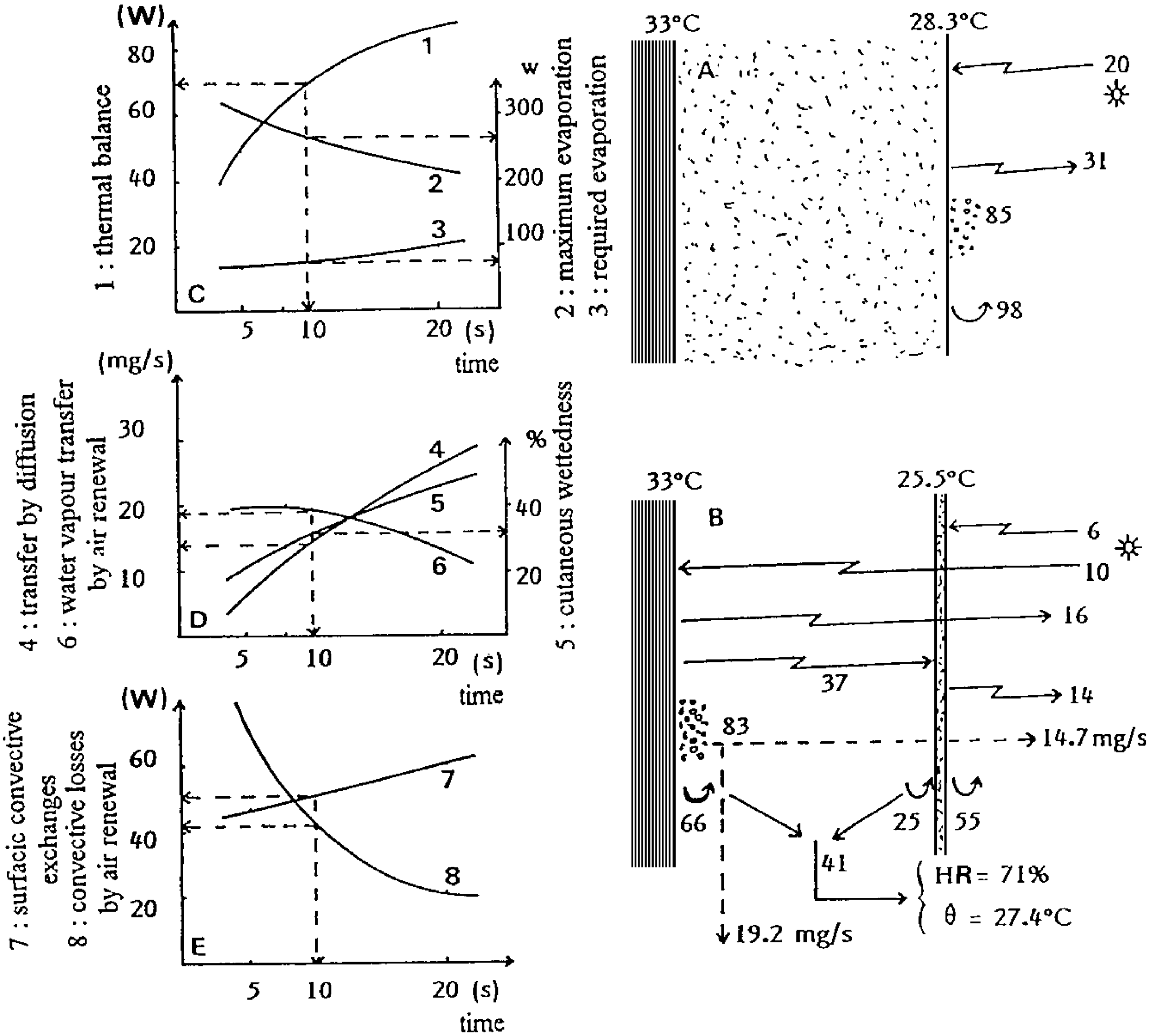


Figure 4. The various temperatures (°C) and energetic transfers (W for the whole clothed body) for three equivalent systems.

• half of the radiative transfers concerns exchanges between skin or underwear and the environment through cloth apertures.

In this example, clothing associates a "static" behavior for two thirds of the dry exchanges, and a "dynamic" behavior for the reminder. The first corresponds to a "basic" insulation (minimum, nearly constant) useful for the environmental conditions. The last can be strongly and swiftly modulated by opening or shutting the garment (buttoning, wrists, collar etc.) to maintain a nearly null balance with varying activity and air ventilation. These two forms of insulation are necessary to adapt humans to their living context. The confined air is warmer and dryer than the outside air, as it is inside buildings, realizing the micro-climate felt (and suitable) by a nude or slightly clothed man.



: radiative exchanges	$T_{air} = T_r = 22°C$	Relative humidity=85%
: convective exchanges	$V_{wind} = 0.3\ m/s$	$\Phi = 50\ W\ m^{-2}$
: air renewal	$\varepsilon_{cl} = 0.56$	$\zeta_{cl} = \zeta_s = 0.2$
: evaporation	$\alpha_s = 0.08$	
: water vapour transfer	$R_V = 30\ Pa\ m^2\ W^{-1}$	$R_V = 2\ Pa\ m^2\ W^{-1}$ (fabric alone)
Activity level = 2 met	$I_{clref} = 0.60$	I_{cl} (act, V_{wind}) = 0.48

Figure 5. Comparison of dry and humid exchanges for PM (A) and NM-thin garment (B) in the same conditions. Variations of the transfers according to the time duration of confinement (C, D, E). The energies are expressed in watts for the whole body, the humid transfers in mg·s^{-1}, the times in seconds.

The next example (*figure 5*) deals with summer climate, and shows the "boundary" behavior of a thin garment: the underwear micro-climate manages half of any hygrothermal exchange. Of course, radiative transfers are indifferent to air renewals, and convective exchanges are strongly influenced by them. As for humid exchanges, the longer the time duration of confinement, the lower is the humid transfer by air renewal etc., but the greater the transfer by diffusion. This last not only depends on the resistance, but also on the difference between the vapour pressures in the confined and outside airs. The required evaporation is no much influenced by the time duration of confinement: the maximum evaporation in the confined air strongly varies and modifies the skin wetness. Activity and air velocity act on the dry exchanges, and consequently, on the thermal balance, in the same time as they act on the evaporating power of the air.

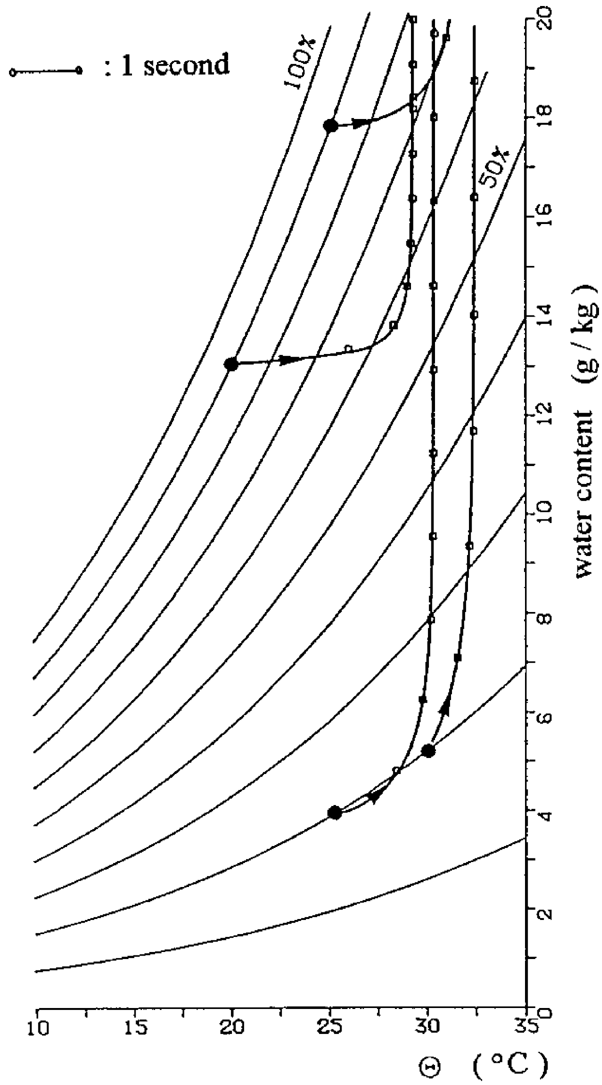


Figure 6. Clothing as a help for evaporation in saturated humid climate. Confined air more humid than outside air in dry climate. Hygro-thermal state of the confined air according to the time of confinement (in seconds) [5].

The hygro-thermal state of the confined air confirms the interest for clothing in tropical climates (*figure 6*):

- against too dry air, clothing not only behaves as a white barrier rejecting solar radiations, but maintains a more humid environment near the skin, and that is more pleasant to feel;
- convective losses being small if the air temperature is close to the mean skin temperature (36 °C), a few degrees in more for the confined air temperature are felt with indifference. Small heating of the confined air moves this air away from saturation in too humid an air: thus, the confined air can be charged with more water vapour, and wick and fan effects can then be efficient [5]. In fact, the problem of comfort in a warm humid climate lies on the possibility in evaporating, more than on the warmth of the air, or on the amount of sweat to evaporate.

5. CONCLUSION

NM, with its four options, constitutes a tool for the conception of clothes and fabrics, and for the study of comfort (not approached in this paper). Of course, some expressions or coefficients can be discussed, and modified if necessary. The aim of this work was, however, to obtain a more realistic description of the heat and mass transfers through clothing than it is in "pseudo-passive" models. With NM, clothing appears much more as an interface which creates a suitable micro-climate near skin, than as an insulation. Bringing together dwelling and clothing studies, it resembles glazing more than a wall.

NM can be improved in several ways:

- introduction of damping and wick effects (other evaporating areas, different resistivities),
- considering a difference between permeodynamical and parietodynamical ventilations (heating and wetting the entering air, action on clothing for the first),
- considering different solar and IR absorptivities for the inner and outer sides of the garment,
- considering garments made of several layers,
- considering garments with specific properties.

The role attached to the garment seems reduced in NM. But these improvements lead to consideration of new parameters in addition to the insulation: suppleness, transparency, wick and stick properties etc. Clothing is really a complex system to keep man comfortable under various and varying activities and environments.

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