No. 2135

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Moisture Permeation of Clothing - A Factor Governing Thermal Equilibrium and Comfort

THE QUANTITATIVE EVALUATION of the many factors associated with the transfer of heat caused by the evaporation of body sweat has been a subject of major interest over the past three decades. Skin wettedness (Ref 7) was early observed as a significant factor associated with the sense "pleasantness" and more recently with "comfort" of the environment (Ref 8, 9, and 21). Physiologists (Ref 2 and 22) have observed before from their experiments that the same environmental factors that govern the transfer of heat by convection from man's skin surface also govern the transfer of heat by evaporation. Engineers on the other hand have long recognized from mass-transfer theory that the ratio of the mass transfer coefficient by evaporation to the heat transfer coefficient by convection is a constant and is known as the "Modified Lewis Relation" (Ref 1, 12 and 17). It is thus possible to replace the evaporative heat loss term in the heat balance equation by a term containing the skin wettedness, the convective transfer coefficient, and the vapor pressure gradient from the skin to the ambient air. Such a new heat balance equation has been validated for a man whose skin surface is completely wet (Ref 2, 12 and 15).

When subjects are clothed, mass-transfer theory becomes more complex – especially in cases where absorption and evaporation of water by clothing occurs, where the presence of a frost line and a condensation line exist (Ref 4, 6 and others), which possibly may cause an evaporative cyclic heat pump (Ref 3).

Resistance of clothing to water vapor transfer and its effect on the efficiency of the regulatory sweating are factors that has been under continuous investigation for many years (Ref 4, 6, 10, 14, 15, 16 and 23). Some authors have recognized the similarity between the resistance of clothing to heat transfer and to vapor transfer (Ref 4, 9 and 12) and have introduced this concept into the heat balance equations. Woodcock (Ref 23) has proposed a "permeability index," as a measure of the resistance of clothing to water vapor. Recently Nishi and Ibamoto (Ref 15) have proposed a factor, "permeation efficiency". This latter factor is theoretically somewhat similar to Burton's (Ref 4) concept which noted the parallel between efficiency of clothing to transient heat and to its efficiency to transient water vapor.

The purpose of the present paper is to develop a practical relationship between the resistance of clothing to water vapor and its transfer from the

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*Partially supported by National Institutes of Health Grant #ES-00354-02

sweating skin surface. The heat balance equation for clothed subjects under the condition where all evaporation occurs at the skin surface will be validated by applying the fundamental mass transfer phenomenon of naphthalene sublimation rather than by water evaporation.

THEORY

The heat of vaporization of body water is the principal avenue of man's heat loss necessary to maintain normal body temperature in warmer environments. It occurs by evaporation of secreted sweat and moisture on the skin surface and by the mass transfer of the water vapor through the clothing to the ambient environment. For purposes of simplicity we will assume that the wall and air temperature of the environment are equal. The heat balance equation* for thermal equilibrium may be written

$$M = E_{res} + E_{skin} + (R+C) \qquad (1)$$

where all energy units are expressed in w/sq m and the body surface area is in sq meter and measured by the DuBois formula; M is the net metabolic heat produced by the body; E_{res} is the respired heat loss; E_{skin} is the heat lost by evaporation on the body's skin surface, and (R+C) is the dry heat exchange by radiation and convection from the clothing surface.

The term for dry heat exchange can be described by the following relation

$$(R+C) = f_{cl} \cdot h\,(\overline{T}_s - T_a), \quad W/m^2 \qquad (2)$$

$$\text{where} \quad h = h_r + h_c, \quad W/(m^2 \cdot {}^\circ C) \qquad (3)$$

$$f_{cl} = I_a/(I_a + I_{cl}), \quad \text{dimensionless} \qquad (4)$$

$$\text{or} \quad = h_{cl}/(h + h_{cl}) \qquad (5)$$

Energy will be express in "watt" and temperature scale will be C. For those interested in conversion of metric, English and practical units;

1 W/m^2 = 0.86 kcal/(m^2. hr) = 0.317 Btu/(ft^2. hr)

1 W/(m^2. C) = 0.86 kcal/(m^2. hr. C) = 0.176 Btu/(ft^2.hr. F)

1 clo unit = 0.155 m^2.°C/W = 0.18 m^2.hr. C/kcal = 0.88 ft^2.hr. F/Btu

1 mps = 200 fpm ≈ 2.24 mph

In the above equations (1–5)

$\overline{T}_s$ = the mean skin temperature, C

h_r = the linear radiation heat transfer coefficient, W/(m^2. C)

h_c = the convective heat transfer coefficient and is a function of air movement, W/(m^2. C)

h = the combined heat transfer coefficient for heat exchange from surface of the clothing, W/(m^2. C)

h_{cl} = clothing conductance, W/(m^2. C)

f_{cl} = $h_{cl}/(h + h_{cl})$ and is Burton's efficiency factor for clothing (Ref 11),

I_{cl} or $1/h_{cl}$ = the insulation of clothing, m^2. C/W

and

I_a or 1/h = the insulation of the air. m^2. C/W

Eq 2 describes the heat loss from the skin surface at $\overline{T}_s$ to the environment at T_a. The "drive" and its direction is described by the gradient $(\overline{T}_s - T_a)$.

For the case of vapor transfer from the skin surface to the ambient air the "drive" is the vapor pressure difference from the skin surface to the ambient air. Analogous to Eq 2 we may write (Ref 15)

$$E_{skin} = w.\ f_{pcl} \cdot h_e \cdot (P_s - \phi_a\, P_a). \qquad (6)$$

where

w = the fraction of the total surface that is wet (Ref 7, 15) (wettedness), dimensionless

h_e = the evaporative heat transfer coefficient for water vapor and is same function of air movement as is h_e above, (Ref 12, 17) W/(m^2.mm Hg)

P_s, P_a = the saturated vapor pressure at $\overline{T}_s$ or T_a, mm Hg

The algebraic symbols used in the present paper conform with those proposed for thermal physiology by the American Physiological Society and the International Union of Physiological Sciences based on Systeme Internationale (SI). (ref. 25).

ϕ_a = relative humidity of the ambient air (fraction) dimensionless

and

f_{pcl} = $h_{ecl}/(h_e + h_{ecl})$, which is "permeation efficiency factor". (7)

Note the analogy between the terms used to define f_{cl} and f_{pcl}. In Eq 7

h_{ecl} = diffusive heat transfer coefficient through clothing. W/(m^2.mm Hg)

The reciprocals of h_e. and h_{ecl} are the resistances of air and clothing to the transfer of water vapor. If $I_{ea} = 1/h_e$ and $I_{ecl} = 1/h_{ecl}$, then

$$f_{pcl} = I_{ea}/(I_{ea} + I_{ecl}). \quad (8)$$

The insulation of the clothing itself I_{cl} may be measured during thermal equilibrium by the ratio, $(\overline{T}_s - \overline{T}_{cl}) / (M - E_{res} - E_{skin})$, where $\overline{T}_{cl}$ is the clothing surface temperature. If the clothing has an average thickness L_{cl} (meter) and is homogeneous with a thermal conductivity k_{cl} in W/(m. C), then the insulation of clothing is expressed as

$$I_{cl} = L_{cl}/k_{cl} \quad m^2. C/W \quad (9)$$

As a simplification, let us imagine a still air layer surrounding the skin with thickness L_{eq}, whose insulation is identical to the layer L_{cl} of the clothing itself. Then, by the relation

$$L_{eq} = k_{air}\, I_{cl} \quad (10)$$

From Eq 9 above

$$L_{eq} = (k_{air}/k_{cl}) \cdot L_{cl} \quad (11)$$

We will now assume that this equivalent still air layer, L_{eq}, has the same resistance to water vapor as the clothing itself, when it is transported by molecular diffusion from a surface at P_s to another surface at $\phi_{cl}P_{cl}$. According to *Stefan's Flow* in the absence of other potential gradients, the rate of diffusive vapor flow $\dot{m}$ through an imaginary still air layer, L_{eq}, can be expressed by

$$m = D_w(P_s - \phi_{cl}P_{cl}) / [L_{eq}R_w(\overline{T}_s + 273°)] \quad (12)$$

D_w = mass diffusivity into air m^2/hr

R_w = gas constant for water vapor, mm Hg.m^3/(kg.°K)

$\overline{T}_s + 273°$ = absolute temperature of skin surface, °K

$\phi_{cl}\, P_{cl}$ = vapor pressure at clothing surface. mm Hg

In a manner similar to heat conductance, the diffusive heat transfer coefficient through the clothing layer, h_{ecl}, may be written

$$h_{ecl} = \lambda.\dot{m}/(P_s - \phi_{cl}\, P_{cl}), \quad (13)$$

where λ is the latent heat for vaporization in W.hr/kg. By eliminating $(P_s - \phi_{cl} P_{cl})$ with Eq 12 and L_{eq} with Eq 11 it follows

$$h_{ecl} = \lambda.D/[k_{air}\, I_{cl}R_w(\overline{T}_s + 273°)] \quad (14)$$
W/(m^2.mm Hg)

and by substituting numerical values from Table 1 for practical sea level conditions

$$h_{ecl} = 2.39/I_{cl} \quad W/(m^2.mm\ Hg) \quad (15)$$

In Eq 14 the only physical property of the clothing used to define h_{ecl} is the insulation I_{cl} itself. For our simplification the effect of moisutre absorption capacity and porocity or weaving density of material, all of which theoretically affect the diffusive mass flow through clothing, are ignored as a first order of accuracy.

The evaporative heat transfer coefficient, h_e, is related to convective heat transfer coefficient, h_c, by

$$h_e = 2.2\, h_c, \quad (16)$$

where 2.2 is the modified Lewis relation in C/mmHg (Ref 12 and 17). The probable relationships between h_c and air movement v (m/s) are indicated in the footnote to Table 1.

The permeation efficiency, f_{pcl}, can be theoretically evaluated by substituting Eq 15 and 16 in Eq 7, Values of f_{pcl} so calculated for different I_{cl} and air movements are shown in Fig. 1.

EXPERIMENTAL RESULTS

A series of experiments were designed to measure the permeation factors derived from Eq 7 and 14 for the various air movements and thermal insulations. There are many difficulties in accurately measuring the rate of weight loss caused by evaporation of water. The process of sublimation, i.e. from a solid state to a vapor state, has been of particular

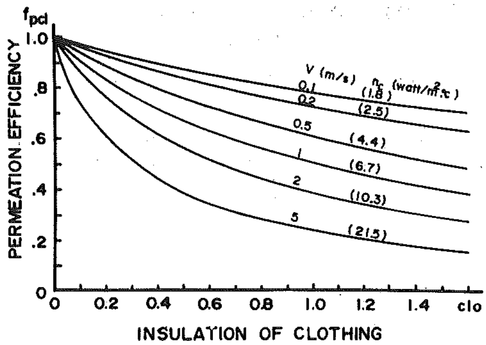

Fig. 1 The relation between the theoretically derived permeation efficiency factor for water vapor transfer, f_{pcl}, clo value and the air movement. The factor, f_{pcl}, takes the ultimate value of 1.0 in the unclothed condition at any air movement.

interest as a research tool for predicting the heat or mass transfer relation. The rate of sublimation is relatively easy to measure by observing the rate of weight change of the solid on a balance. As a sublimating material in the present study the authors used naphthalene, which many investigators (Ref 13, 18 and 20) have employed previously. Naphthalene has these advantages in comparison to water vapor;

1) It remains solid at normal atmospheric air temperature and sublimates at experimentally desirable rates at these temperatures,

2) Its surface partial pressure can be treated as saturated at its surface temperature,

and

3) The partial pressure of the naphthalene is zero away from the surface.

The physical properties of water vapor and naphthalene are listed in Table 1.

Our experimental apparatus consisted of two identically shaped plates – one of copper and the other of naphthalene and they are illustrated in Fig. 2. The test section A 10 (cm) x 10 (cm) area was surrounded by a guard plate B. The copper plate was heated and mounted on top of a thick polystyrene block. The copper itself was painted blackmat. This assembly was used to measure the thermal insulations (resistances) of the boundary layer,

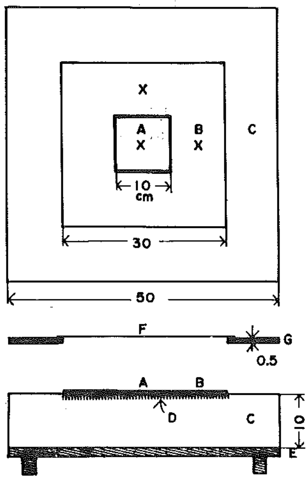

Fig. 2 Design of experimental apparatus. This apparatus, used for the measurement of thermal insulation and sublimation, consists of a pair of two identical plates – heated copper plate and naphthalene plate.
A: heated copper plate or naphthalene plate 10 (cm) x 10 (cm).
B: heated copper guard or naphthalene guard plate 30 (cm) x 30 (cm) with 10.2 (cm) x 10.2 (cm) opening.
C: polystyrene base 50 (cm) x 50 (cm).
D: resistance wire for heat supply.
E: 1 (cm) plywood base.
F: black cotton cloth (weight 120 gram/m^2).
G: hardboard frame.
X: thermocouple.

I_a, and of the test clothing layer, I_{cl}. Heat was always supplied electrically to sections A and B, so their temperatures were equal and uniform. Surface temperatures were measured by copper-constantan thermo-couples by a recording voltmeter or manual potentiometer. The air temperature 10 cm above the plate was also measured by a thermocouple. Air movement was so controlled by an electric fan that the convective heat transfer coeefficient, h_c, at the plate or clothing surface was 1.9, 4.8 and 7.8 watt/(m^2.°C) respectively. The experimental room was maintained at a uniform temperature of 25°C within $\pm$ 0.1°C.

The thin, flat, naphthalene plates with guard ring were cast identical in area to the copper plates and were approximately 2 mm thick. The lower side of

TABLE 1

PHYSICAL PROPERTIES CONCERNING WATER AND NAPHTHALENE VAPOR TRANSFER (ref. 24)

(1 atm.)

	WATER VAPOR	NAPHTHALENE VAPOR	UNITS
Mass diffusivity into air: D	$0.0784\left(\frac{T}{273}\right)^{1.8}$	$0.0185\left(\frac{T}{273}\right)^{2}$	m^2/hr
at 33°C	0.096	0.023	m^2/hr
Gas constant: R	3.46	0.487	$mm\ Hg \cdot m^3/(kg \cdot {}^\circ K)$
Molecular weight: M	18 (H_2O)	128.16 ($C_{10}H_8$)	
Latent heat: λ	676	154	W·hr/kg
Diffusive heat transfer coefficient: h_{ecl}	$2.4/I_{cl}$ or $15.5/I_{clo}$	$0.93/I_{cl}$ or $6.0/I_{clo}$	$W/(m^2 \cdot mm\ Hg)$
Mass heat transfer coefficient: h_e	$2.2\ h_c$*	$2.7\ h_c$**	$W/(m^2 \cdot mm\ Hg)$

* Value 2.2 is derived from conventional mass and heat transfer theory and known as Modified Lewis Relation (ref. 12 and 17). Convective heat transfer coefficient h_c is given by following equations (ref. 11), when human body is assumed as a cylinder of 30 cm in diameter and infinite length and the air motion is normal to the axis of the cylinder.

Air movement v (m/s)		
less than 0.2 m/s	$h_c = 5.4\ v^{0.466}$	$W/(m^2 \cdot {}^\circ C)$
between 0.2 and 2 m/s	$= 6.8\ v^{0.618}$	$W/(m^2 \cdot {}^\circ C)$
greater than 2 m/s	$= 5.9\ v^{0.805}$	$W/(m^2 \cdot {}^\circ C)$

** Value 2.7 was derived from the present sublimation experiment for naphthalene.

the castings was sealed from the atmosphere. The surface temperature of the naphthalene plates was assumed to be equal to the ambient air, since the temperature depression caused by the sublimation process was calculated to be maximum 0.1°C. The rate of mass transfer from the test section A was obtained by measuring its rate of weight loss and ranged from a minimum of 10 mg to maximum of 40 mg for each duration of exposure. Changes in the thickness of naphthalene due to sublimation in this range of weight loss are negligible because they are calculated to be under 0.0004 cm in any case.

Layers of black cotton cloth were used to simulate clothing. Various insulations were tested ranging from 0.1 to 1.4 clo.

\# In the equations to follow "primes" refer to Naphthalene.

In the above experimental arrangement the permeation factor for naphthalene transfer, f'_{pcl},# may be obtained directly by the relation

$$f'_{pcl} = \left[\frac{\text{ratio of weight loss from clothed naphthalene plate (kg/hr)}}{\text{to weight loss from unclothed naphthalene plate (kg/hr)}}\right] \qquad (17)$$

It is now possible to evaluate h'_{ech} and h'_c for naphthalene by using Eq 7. h'_c is the measurement for the denominator of Eq 17. Thus the experimental value of h'_{ecl} is

$$h'_{ecl} = f'_{pcl}\ h'_c / (1 - f'_{pcl}) \qquad (18)$$

h'_{ecl} may be also calculated theoretically by Eq 14 above substituting values shown in Table 1.

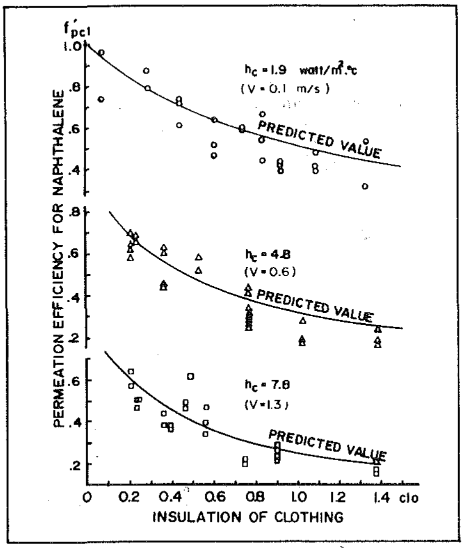

Fig. 3 Comparison between experimentally derived permeation efficiency factors for naphthalene transfer and theoretically predicted values. Air movement was adjusted so that the convective heat transfer coefficient at the testing surface was h_c = 1.9, 4.8 and 7.8 W/(m². °C), which values are equivalent to 0.1, 0.6 and 1.3 m/s, respectively.

Comparison of experimentally and theoretically derived values of f'_{pcl} are shown in Fig. 3. The figure shows good correspondence between theory and experiment and confirm our general assumption above that the obstruction by the same clothing fabric to molecular motion is negligible.

DISCUSSION

The question now arises, how well does naphthalene simulate the process of water vaporization? Do equations (7) and (14) apply in both cases? So in (Ref 20) has shown that, by using a disc size similar to that used by Powell (Ref 16) for water vaporization, the physical factors governing sublimation of naphthalene closely matched the vaporization data for water. On the basis of this possible similarity of mass transfer processes, can the factor for water vapor permeation for clothing be predicted from experimentally derived data for naphthalene?

The following ratios describe theoretically the relative magnitude of mass transfer processes for naphthalene and water vapor and are based on Eq 14 and numerical values shown in Table 1.

$$h_{ecl}/h'_{ecl} = 2.564\,, \tag{19}$$

$$h_e/h'_e = 0.813\,. \tag{20}$$

Eqs 15, 16, 19 and 20 may be used in Eq (7) to derive the ratio of permeation efficiency factor for water vapor, f_{pcl}, and for naphthalene, f'_{pcl}, as follows

$$f_{pcl}/f'_{pcl} = \left(1 + \frac{h_c \cdot I_{cl}}{0.507 + 0.465\, h_c\, I_{cl}}\right), \tag{21}$$

or when the insulation of clothing, I_{clo}, is expressed in clo units,

$$f_{pcl}/f'_{pcl} = \left(1 + \frac{h_c \cdot I_{clo}}{3.27 + 0.465\, h_c \cdot I_{clo}}\right). \tag{22}$$

The relation between permeation values for water vapor derived with Eq 21 or 22 and those theoretically predicted by Eq 7 and 14 are shown in Fig. 4.

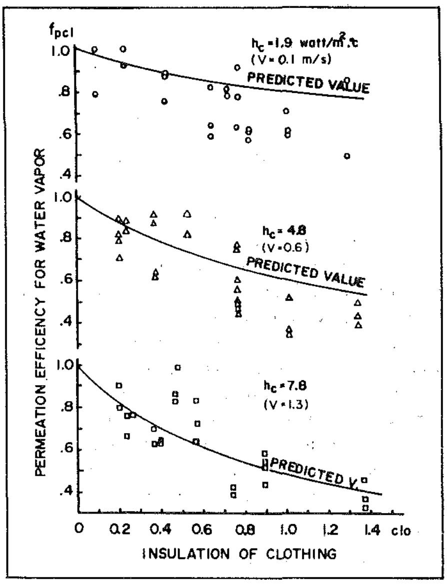

Fig. 4 Comparison between permeation efficiency factors for water vapor transfer and theoretically predicted values. Permeation efficiency factors for water vapor were derived from naphthalene data, shown in Fig. 3, using the analogy of mass transfer processes.

Although the comparison between experiment and theory is not as good as it was with naphthalene alone, naphthalene simulation may be used as a first approximation to describe the process of sweat vaporization through man's normal clothing. There are still some limitations in evaluating the effect of such physical properties as porocity or weaving density. In the extreme case of non-permeable clothing made of rubber or vinyl film Eq 14 has no significance, as diffusive heat transfer coefficient, h_{ecl}, should take the ultimate value of zero and be independent of clothing insulation. This case applies only to a skin tight suit completely covering the man. For loose fitting impermeable outer garments h_{ecl} may not be zero because of an "evaporative cyclic heat pump" (Ref 3).

In the practice of air conditioning for comfort, when porous and loose fitting clothing is usually worn, Eqs 7 and 15 can be applied directly to predict the permeation efficiency for vaporization of sweat from the skin surface. The following two equations can be used with reasonable accuracy in any heat balance which includes both the terms f_{cl} and f_{pcl};

$$f_{cl} = 1/[1 + 0.155\,(h_r + h_c)\,I_{clo}\,], \qquad (23)$$

and

$$f_{pcl} = 1/(1 + 0.143\,h_c \,.\, I_{clo}), \qquad (24)$$

where I_{clo} is expressed in clo units. The above relations are in a form suitable for use in a computer model of the environment, such as we have suggested previously (Ref 9).

In 1962 Woodcock proposed a "permeability index" (i_m) as a measure of the resistance of clothing to water vapor. His index was used to describe the evaporative heat loss from a clothed human body in the equation

$$E = i_m \,.\, S \,.\, (P_s - \phi_a P_a)/(I_a + I_{cl}), \qquad (25)$$

where

i_m = Woodcock's permeability index,

S = a constant equal to 2°C/mmHg. This factor corresponds to the Lewis relation for h_e/h_c = 2.2°C/mmHg as shown in Eq 16,

and P_s, P_a, ϕ_a, I_{cl} and I_a are the same as defined above. By comparing Woodcock's Eq 25 to out Eq 6 we can relate his permeability index, i_m, with our "permeation efficiency factor", f_{pcl}, as follows

$$i_m \approx w \,.\, f_{pcl} \,.\, h_c \,.\, (I_a + I_{cl}), \qquad (26)$$

or from eq. (4)

$$i_m \approx w \,.\, (I_a \,.\, h_c) \,.\, (f_{pcl}/f_{cl}). \qquad (27)$$

For completely impermeable clothing i_m, f_{pcl} and h_{ecl} all equal zero. For an unclothed subject f_{pcl} and f_{cl} are unity and Eq 27 becomes

$$i_m \approx w \,.\, (I_a \,.\, h_c) \text{ or } w \,.\, h_c/(h_r + h_c). \qquad (28)$$

i_m thus would be theoretically unity, when $w = 1$ and $h_c >> h_r$, as is the case for a sling type wet bulb thermometer. For observed values of i_m on a sweating manikin, where $w = 1$, f_{pcl} can be predicted from Eq 26 by

$$f_{pcl} = i_m/[h_c \,.\, (I_a + I_{cl})]. \qquad (29)$$

Goldman (Ref 10) has observed a value of i_m = 0.5 for jacket and trousers (Army fatigues); his corresponding h_c was 2.91 W/m^2.°C; and his $I_a + I_{cl}$ = 1.33 clo or 0.206 m^2.°C/W. For this fatigue uniform, which is somewhat similar to the standard Kansas State University clothing, his predicted value for our f_{pcl} would have been 0.83. We reported a predicted value of 0.82 for the KSU clothing (Ref 9).

Summary

(1) A "permeation efficiency factor", f_{pcl}, has been defined that describes the "cooling" efficiency of sweating on the skin surface for a clothed human body.

(2) The factor, f_{pcl}, has been derived theoretically in terms of the convective heat transfer coefficient, h_c, and the thermal insulation of the clothing, I_{cl}.

(3) Sublimation of naphthalene has been used to simulate the process of diffusive mass flow of water vapor from a skin surface through clothing to the ambient environment.

(4) Experimental data derived by naphthalene sublimation have validated the theoretically predicted values of f'_{pcl} for naphthalene. By comparing the physical properties of naphthalene and water vapor, the same experimental data may be used to validate theoretically predicted value of f_{pcl} for water vapor.

(5) For clothing normally worn for comfort the "permeation efficiency factor" may be predicted with reasonable accuracy from its *clo* value and from the ambient air movement present (see Fig. 1).

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DISCUSSION

G. M. RAPP (John B. Pierce Foundation, New Haven, Conn.): Dr. Nishi, congratulations on a very interesting approach to a difficult problem. Your present theory on the permeation of moisture through clothing apparently assumes that the evaporation process itself occurs at the skin surface itself. How would the values of f_{cl} and f_{pcl} be affected, if the evaporation occurs within the clothing layers?

DR. NISHI: Our generalized theory, as presented here, is an approximation for a complex system of moisture permeation through clothing. As one can easily recall, when in a hot environment, some percentage of secreted sweat may infiltrate the clothing by capillary action and vaporize somewhere within its layers.

To answer your question, let us suppose all the secreted sweat evaporates on an imaginary layer of halfway between the skin and outer clothing surface.

For example, for the steady state body heat exchange the following assumptions may be accepted.

(1) The clothed man is in a still air environment and his environmental conditions are set as:

uniform ambient air temperature	32 C
relative humidity	50% or 18mmHg
combined heat transfer coefficient	$h = 8.1$ W/m^2 C
convective heat transfer coefficient	$h_c = 2.9$ W/m^2 C
dry clothing conductance	$h_{cl} = 10.8$ W/m^2 C (0.6 clo)
heat loss from skin surface	$M - E_{res} = 50$ W/m^2

(2) Dry clothing model; all the secreted sweat vaporizes at the skin surface and permeates through dry clothing.

Skin wettedness is $w = 0.30$

(3) Wet clothing model; all the secreted sweat infiltrates halfway through the clothing layer by capillary action and then vaporizes. The thermal insulation of the wetted half layer decreases to 1/3 of dry one.

Wettedness of the imaginary clothing layer where vaporization occurs takes the same value as skin wettedness as $w = 0.30$. Permeation and thermal efficiency factors (f_{pcl}, f_{cl}), skin temperature (T_s), temperatures of inner imaginary layer and outer clothing surface (T_i, T_{cl}), vapor pressures (P_s, P_i) and heat losses by R+C and sweat evaporation (E_{skin}), all of which are values for a thermal equilibrium, may be calculated for both models as:

Dry Clothing Model

f_{pcl}	f_{cl}	T_s	P_s	T_i	P_i	T_{cl}	R+C	E_{skin}
0.80	0.57	35.0	42			33.7	14	36

Half Wet Clothing Model

f_{pcl}	f_{cl}	T_s	P_s	T_i	P_i	T_{cl}	R+C	E_{skin}
0.89*	0.73*	34.8		34	40	33.5	12	38

*Being available between the imaginary layer of the half way (P_i, T_i) and ambient air ($\phi_a P_a$, T_a).

Summary: For the half wetted clothing, both permeation f_{pcl} and thermal f_{cl} efficiency factors increase. Then, in this particular example in spite of the decrease in the vapor pressure difference between the vaporizing layer and ambient air ($P_i - \phi_a P_a$) the rate of skin evaporation remains almost constant with a consistent skin temperature.

For a normal light clothing man usually wears, our permeation efficiency factor may be used regardless of a possible evaporation within the clothing layers to predict the heat loss by sweat vaporization with reasonable accuracy.