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A Technological Study on Moisture Permeation Resistivity of Clothing

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Abstract

Garments not only work as thermal resistivity in the presence of radiation and convection heat release from the body, but also play a role of moisture permeation resistance against perspiration heat release. Whereas clo values may be generally used as a unit for thermal resistivity, a practical unit for moisture permeation resistivity has not been established as yet.

The authors, using a technological approach, derived an index for the quantitative evaluation of moisture permeation of garments based on heat transfer and mass transfer theory. In addition using a dry and a wet cylinder, model experiments were carried out to verify its effectiveness. Further, several moisture permeation units set forth previously by other workers were mentioned and a comparison between the present unit and its relatonship were discussed in the present paper.

1. Introduction

The body heat produced by metabolic action is released from the garment surface by convection and radiation and heat release occurs via the pathway of perspiration permeating through garments, respiration and clothing ventilation and as a result thermal equilibrium reaches a steady state between the body and the environment. Part of the insensible perspiration and sweat is released along with ventilation under the garments and the remainder passes through the garments and is released into the environment. The garment acts as a heat resistant material and also forms a resistance to moisture. Compared with the studies and results of heat resistance represented by clo unit, applicable criteria for the quantitative assessment of moisture permeation of clothes have not been established. The authors based on the theories of heat transfer and moisture transfer, have presented a theoretical study on moisture permeation of clothes related to body temperature control and thermal sensation using a technological approach. In addition model experiments were performed using a cylinder in an attempt to verify the effectiveness and at the same time a comparison was made between the index by Woodcock or by Nishi et al. and the present index.

2. Basic theory

The metabolic energy produced in the body is released by convection, radiation,

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perspiration, respiration, ventilation under garments and external mechanical work and a steady state thermal equilibrium between the human body and the environment is given by the following equation.

$$H=H_d+H_e+H_n+H_v+H_w=H_d+ML+H_n+H_v+H_w \tag{1}$$

where H: net rate of metabolic energy
H_d: convective and radiant heat loss
H_e: evaporation heat loss
H_n: respiration heat loss
H_v: heat loss by clothing ventilation
H_w: external mechanical work
M: rate of diffusive vapor flow through clothing
L: latent heat of water evaporation.

In an environment where radiant temperature is equal to air temperature, dry heat loss H_d in the above equation may be given as follows using the clo unit for the thermal resistance of clothes.

$$H_d=\frac{1}{0.18G+\dfrac{1}{\alpha_r+\alpha_c}}(T_s-T_a) \tag{2}$$

where H_d: convective and radiant heat loss [kcal/m^{2}h]
G: clo unit [$-$] (1 clo$=$0.18[m^{2}h deg/kcal])
α_r: radiant heat transfer coefficient [kcal/m^{2}h deg]
α_c: convective heat transfer coefficient [kcal/m^{2}h deg]
T_s: skin temperature [°C]
T_a: air temperature (=radiant temperature) [°C]

On the other hand, wet heat loss H_e may be expressed as follows by introducing a moisture permeability coefficient of clothing,

$$H_e=\frac{\kappa}{0.18G\eta+\dfrac{1}{\alpha_c}}(X_s-X_a) \tag{3}$$

where H_e: evapororation heat loss [kcal/m^{2}h]
κ: modified Lewis relation factor [deg(°C)/(g/kg)]
X_s: humidity ratio of skin [g vapor/kg dry air]
X_a: humidity ratio of air [g vapor/kg dry air]
η: moisture permeability coefficient [$-$].

The rate of diffusive vapor flow M from the skin to the outer surface of clothes has already been established from the analogy of heat transfer and moisture transfer[1].

$$M=\frac{1}{\dfrac{l_g R_w(T_s+273)}{D_w}}(X_s-X_g) \tag{4}$$

where X_g: humidity ratio of clothing surface [g vapor/kg dry air]
l_g: thickness of clothing [m]
R_w: gas constant for water vapor [(g/kg)m^3/g °k]
D_w: mass diffusion coefficient of water vapor into the air [m^2/h].

Equation (4) is only applicable to diffusion of water vapor into the air. If the mass diffusion coefficient of water vapor D penetrating the complicated space formed by fibers of the garment and air in an actually clothed state is known, the rate of diffusive vapor flow M may be expressed by equation (5) in a similar manner to equation (4).

$$M=\frac{1}{\dfrac{l_g R_w (T_s+273)}{D}}(X_s-X_g) \tag{5}$$

where D: mass diffusion coefficient of water vapor into clothing [m^2/h]. However, in order to accept equation (5) as it is, since it is impossible to obtain actual data of mass diffusion coefficient D, the authors have applied the concept of ratio of air volume in clothing μ[2]. According to the thinking of Fig. 1 in which clothes are assumed to be homogeneous, the following discussion was made. The mass diffusion coefficient of water vapor into wood consisting of high molecular fibers shows an inversely proportional decrease to the density. The mass diffusion coefficient into high density wood as compared with that of mass diffusion coefficient into the air is much smaller in the order of 10^{-6} less. Therefore, it may be surmized that the mass diffusion coefficient into actual fibers in wood is infinitesimal. It may also be assumed that the same would hold true in the case of clothes, it may be conceived that the fibers of the cloth itself acts as a moisture insulation, and it may be also considered that the air contained between fibers and the air layer among garments are penetrated by water vapor, therefore the diffusion of water vapor into the air would be influenced by the ratio of air volume in clothing μ, and the following equation may be assumed.

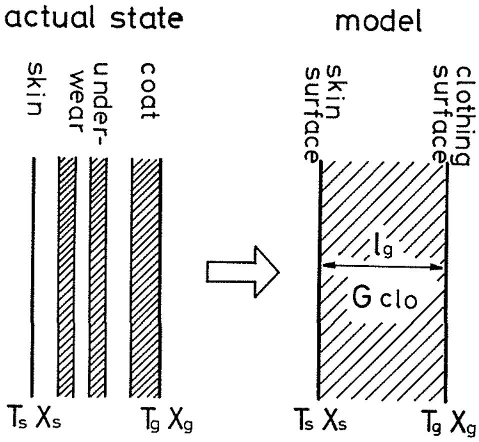

Fig. 1 Model of clothed state.

$$D=D_w\mu \tag{6}$$

where μ: ratio of air volume in clothing [$-$].

Substituting the relationship of equation (6) into equation (5), we get the rate of diffusive vapor flow M in the following equation.

$$M=\frac{1}{\dfrac{l_g R_w (T_s+273)}{D_w\mu}}(X_s-X_g) \tag{7}$$

Further, with regards to the ratio of air volume in clothing, μ was taken as

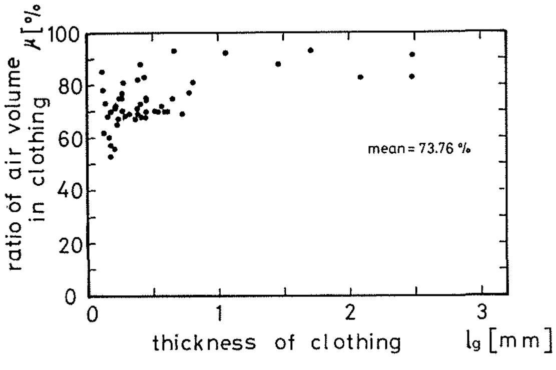

Fig. 2 Ratio of air volume in clothing[2].

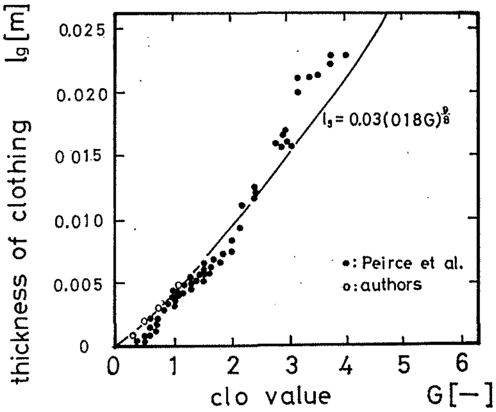

Fig. 3 Relationship between thickness of clothing and clo value.

$\mu \fallingdotseq 0.7$ based on actual measurements as shown in Fig. 2[2].

On the other hand, the rate of diffusive vapor flow M may be expressed as follows by using a modified Lewis relation factor and moisture permeability coefficient η.

$$M=\frac{\kappa}{\eta(0.18GL)}(X_s-X_g) \tag{8}$$

From equation (7) and equation (8), equation (9) may be derived as follows.

$$\eta=\frac{\kappa R_w(T_s+273)l_g}{0.18GLD_w\mu} \tag{9}$$

From the results of Peirce et al.[3] and the present authors, the relationship of garment thickness and clo value may be simulated by the simplified equation.

$$l_g=0.03(0.18G)^{9/8} \tag{10}$$

When Nishi's permeation efficiency factor[1] which will be described later is analysed, the relationship $l_g=0.026(0.18\mathrm{G})^1$ may be reckoned backward.

Substituting equation (10) into equation (9), we obtain the characteristic equation (11).

$$\eta=\frac{\kappa R_w(T_s+273)K}{LD_w\mu}\,\frac{(0.18G)^{9/8}}{(0.18G)}=A(0.18G)^{1/8} \tag{11}$$

When the following values obtained within the limits of every day life are substituted into factor A of equation (11), in the final analysis η may be expressed by equation (12)[4,5].

$$\eta=1.644(0.18G)^{1/8} \tag{12}$$

Values used : $\kappa=2.23$ [deg(°C)/(g/kg)]
$R_w=3.114\times10^{-3}$ [(g/kg)m/g °k]
$T_s=30.0$ [°C]
$K=0.03$
$L=0.58$ [kcal/g]
$D_w=0.0946$ [m^2/h]
$\mu=0.7$ [$-$].

The influence of temperature and vapor pressure on factor A in equation (11) may be neglected as a result of investigating Fig. 4 and under normal conditions it is possible to consider it as constant.

From equation (12) the characteristics of moisture permeability coefficient are indicated in Fig. 5.

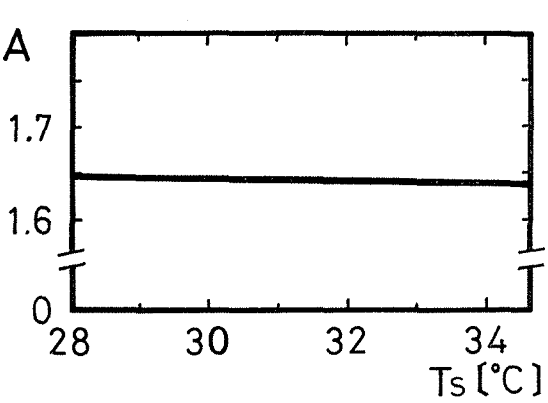

Fig. 4 Characteristics of factor A.

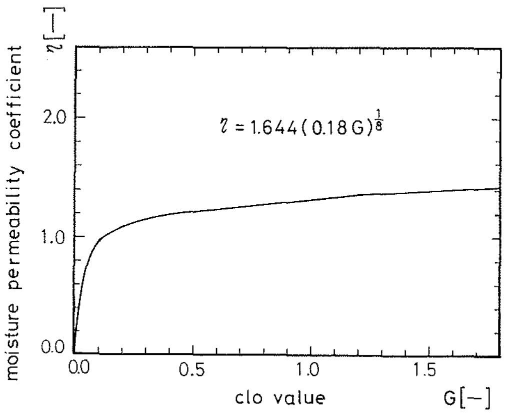

Fig. 5 Characteristics of moisture permeability coefficient η.

3. Experimental apparatus and outline

3.1 Experiment-1

For the verification of theoretical equation (12) of moisture permeability coefficient η, the following experimental apparatus was designed, and the influence of the number of cloth layers from the same material was investigated[5)].

A cylinder (12 cm outer diameter, 80 cm height) was wound and covered with nickel chrome wire and the wire was given a constant electric charge ($H=84\,\mathrm{kcal/m^2h}$). To maintain a sopping wet outer surface several layers of gauze were wound around the surface of the cylinder. The head and the bottom of cylinder were prepared in such a way as to have sufficient heat resistance and further conditions were set to have hardly any ventilation under the garment. In addition a water vessel was placed on the head so that water sucked up would flow down to make a wet cylinder. On the layer of gauze a wire netting was wound and the outer surface was dressed with the cloth to be measured.

In the experiment to obtain η of cloth itself, the distance between the wet cylinder surface and the cloth inner surface was made as small as possible and careful and detailed temperature measurements were made on the cloth inner surface.

The outline of the apparatus is shown in Fig. 6.

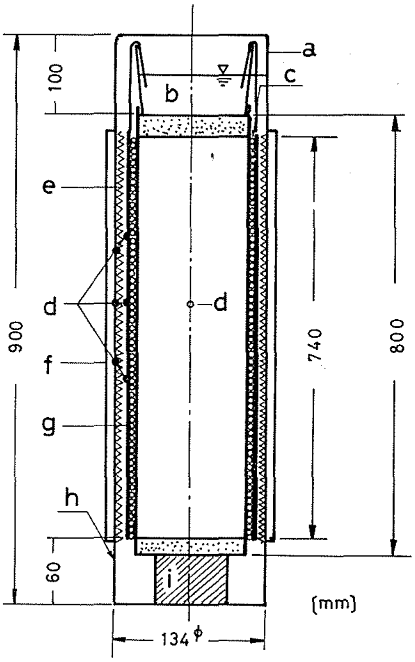

Fig. 6 Sketch of experimental apparatus. (a. covering, b. water tunk, c. nickel chrome wire, d. thermocouple, e. wire netting, f. subject cloth, g. gauze, h. saucer, i. stand)

A wooden enclosure (2.4 × 2.4 × 2.4 m) was constructed in the experimental laboratory and curtains were hung from the ceiling to cover the walls in an attempt to produce an environment where radiant temperature is equal to air temperature, and measurements were made within the enclosure by placing the cylinder on a rotating arm.

3.2 Experiment-2

When η value is calculated in Experiment-1, a hypothesis, in which clo values are eqaul between the clothes clothed on a dry cylinder and a wet cylinder, was made. In the present experiment, a verification of the above hypothesis together with calculation of η value in a clothed state including the cloth and the air layer under the cloth was made. At the same time, the shift of η values in different cloth material and also the influence of air movement were discussed.

Since the lost water volume must be subjected to precise measurements in order to observe the difference between the clo values when the same cloth was wound around the dry cylinder and the wet cylinder, a direct indicating balance (accuracy 0.1 mg) was used. Because of the upper limit of the balance, a small cylinder of the same structure as Fig. 6 was made with an external diameter of

50 mm and a height of 150 mm⁶⁾

The experimental procedure was almost the same as that of Experiment-1, however to ensure a precise measurement of the lost water volume, the control of air movement was done by an electric fan and the actual measurements were made for 2 hours after a steady state was attained.

4. Experimental results

First, the heat balance of the steady state between the experimental cylinder and the environment was considered.

When there is little ventilated air passing under the garment, the heat balance may be given by the following equation and η values may be obtained from the experiment.

$$H=H_d+H_e=H_d+ML=\frac{1}{0.18G+\frac{1}{\alpha_r+\alpha_c}}(T_s-T_a)+\frac{\kappa}{0.18G\eta+\frac{1}{\alpha_c}}(X_s-X_a) \tag{13}$$

Experiment-1 was carried out to investigate the η value of the cloth itself which follows equation (10), and moreover since it was considered that μ is 0.7, the experimental results together with the theoretical solution (12) are presented in Fig. 7.

In Experiment-2, taking into account the heat loss from the ends especially the upper end, the results of the clo value obtained from the small dry cylinder and the small wet cylinder are as shown in Fig. 8.

Under two conditions of high and low air velocity, the clo values of commonly used clothes in everyday life as shown in Table 1 were measured and the results are shown in Fig. 9.

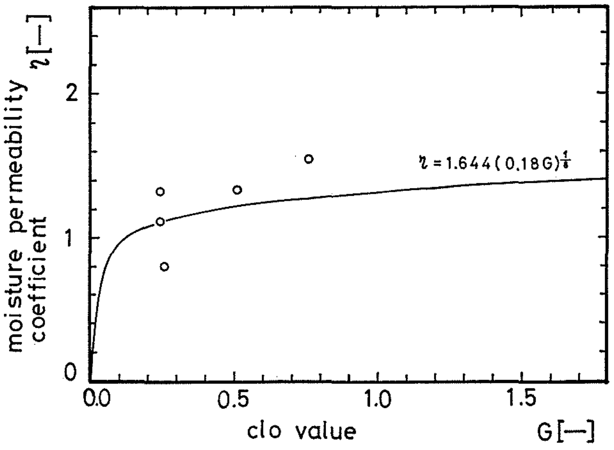

Fig. 7 Relationship between η and clo value.

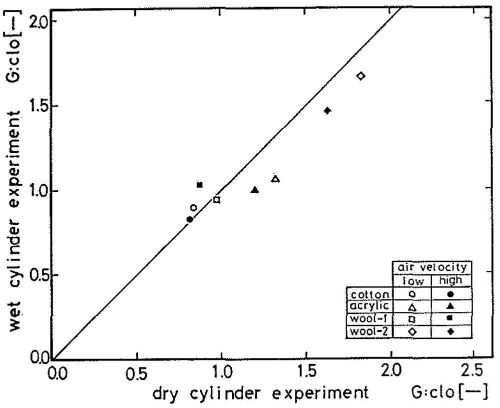

Fig. 8 Comparison of clo values by dry cylinder with by wet cylinder.

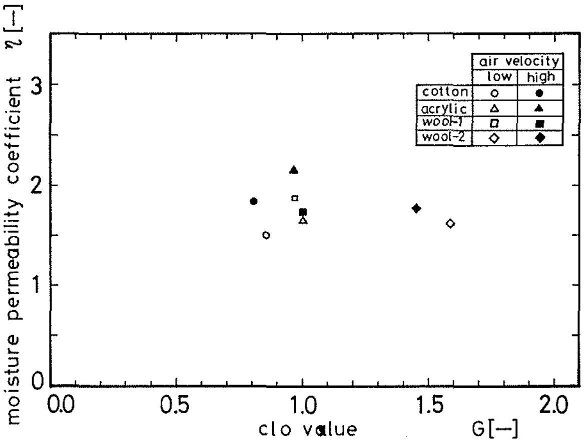

Fig. 9 Relationship between η and clo.

Table 1. Subject clothes

	Weight [g/m^2]	Thickness [m]	Density [kg/m^3]	Textile weave	Use
Cotton	676.46	2.24×10^{-3}	302	Knitting	Underwear
Acrylic	1114.10	4.24	262	Knitting	Coat Sporting wear
Wool-1	681.35	3.50	195	Twill weave	Coat
Wool-2	1362.70	7.00	195	Twill weave	Coat

In the case of small cylnders used in Experiment-2, since the influence of curvature may appear in the heat release phenomenon, equations (14), (15) and (16) which are those of small cylinders corresponding to equations (1), (2) and (3) were used for analysis$^{6)}$.

$$Q=Q_d+Q_e=Q_d+M'L \tag{14}$$

$$Q_d=\frac{2\pi r_g z}{0.18G\left(\frac{r_g}{r_g-r_s}\,ln\frac{r_g}{r_s}\right)+\frac{1}{\alpha_r+\alpha_c}}(T_s-T_a) \tag{15}$$

$$Q_e=\frac{2\pi r_g z\kappa}{0.18G\eta\left(\frac{r_g}{r_g-r_s}\,ln\frac{r_g}{r_s}\right)+\frac{1}{\alpha_c}}(X_s-X_a) \tag{16}$$

where Q : net rate of total heat loss [kcal/h]
Q_d : convective and radiant heat loss [kcal/h]
Q_e : evaporation heat loss [kcal/h]
M' : rate of diffusive vapor flow through clothing [g/h]
L : latent heat of water evaporation [kcal/g]
G : clo [—] (1 clo$=0.18$ m^{2}h deg/kcal)
η : moisture permeability coefficient [—]
α_r : radiant heat transfer coefficient [kcal/m^{2}h deg]
α_c : convective heat transfer coefficient [kcal/m^{2}h deg]
T_s : cylinder surface temperature [°C]
T_a : air temperature (=radiant temperature) [°C]
κ : modified Lewis relation factor [deg (°C)/(g/kg)]
X_s : humidity ratio of wet cylinder [g vapor/kg dry air]
X_a : humidity ratio of air [g vapor/kg dry air]
r_s : radius of cylinder [m]
r_g : radius of outer surface of clothes [m]
z : height of cylinder [m].

5. Discussion

5.1 Discussion of experimets

From the results in Fig. 8, it was shown that the clo value obtained using a dry cylinder showed hardly any difference from that by a wet cylinder, thus confidence of actual measurements of η value in Experiment-1 was obtained. According to Fig. 7 the theoretical and actually measured η value of the cloth alone shows an increasing tendency accompanying the increase in clo value. Since the theoretical solution and experimental result show an approximate coincidence, it may be said that the authors' index may be accepted as a unit for practical use.

The η value of clothing material used widely in everyday life follows the same equation as may be seen in Fig. 9 regardless of kinds of cloth. Although we can not be sure of the results under extremely high air velocities, it was shown that 1 m/sec or under the η value is not influenced by air movement. However, it must be remembered that in most cases of Experiment-2 the rate of air volume in clothing has a rather high rate of $\mu \fallingdotseq 0.9$ and hense an equation which would give the μ value of the cloth itself must be separately dealt with. The relationship of l'_g which is the sum of a series of cloth layers and air layers used in Experiment-2 and clo value G is obtained by equation (17).

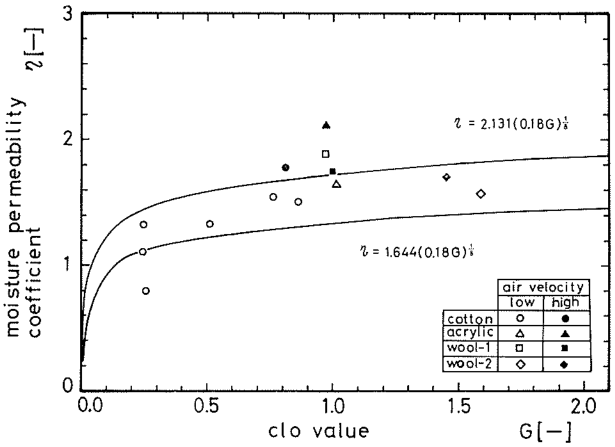

Fig. 10 Relationship between η and clo.

$$l'_g=0.05(0.18G)^{9/8} \tag{17}$$

From equation (17) and from $\mu=0.9$, the theoretical equation for Experiment-2 takes the form of equation (18) and the feasibility thereof may be seen in Fig. 9.

$$\eta=2.131(0.18G)^{1/8} \tag{18}$$

From the above η value may not be decided as a simple matter. When we consider everyday wear, Experiment-1 gives the results for cases where no air layer is present under the cloth. On the other hand since Experiment-2 are cases where the air layer is very large, we may surmise that the actual clothed state fluctuates in between. Fig. 7 and Fig. 9 are brought together and reexpressed in Fig. 10.

When values are over 1 clo for practical purposes $\eta=1.5$ may be used as a fixed number from the width of change in Fig. 10.

5.2 Characteristics of η value

The authors derived coefficient which expresses the moisture permeability by equation (12), but in the course leading to it various hypotheses were made. As to how such assumptions affect η value general tendencies will be investigated here[4]. For the relationship of the clothing thickness l_g and clo value G, Fig. 2 was adopted as a representative form, and the function was limited by $l_g=0.03(0.18G)^{9/8}$. The degree of influence on η values by the changes in exponent 9/8 was investigated.

When equation (10) is expressed in a general form, we have equation (10)′.

$$l_g=m(0.18G)^{(n+1)} \tag{10$'$}$$

The representative particulars of equation (10)′ based on exponent n values are shown in Fig. 11, and the characteristics of η values are shown in Fig. 12.

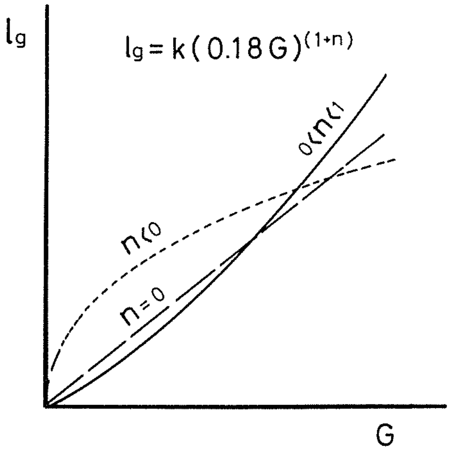

Fig. 11 Influence of exponent n on l_g.

Within a range of $0 \leqq n \leqq 1$ when n

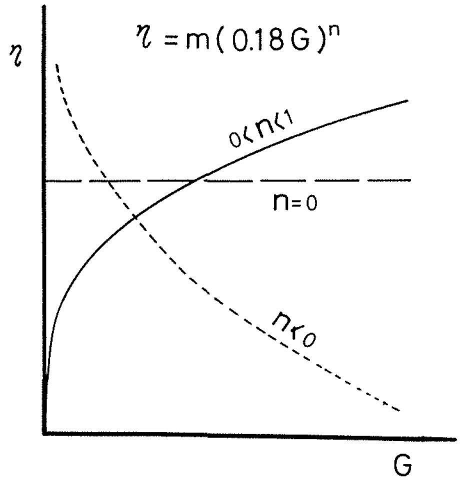

Fig. 12 Influence of exponent n on η.

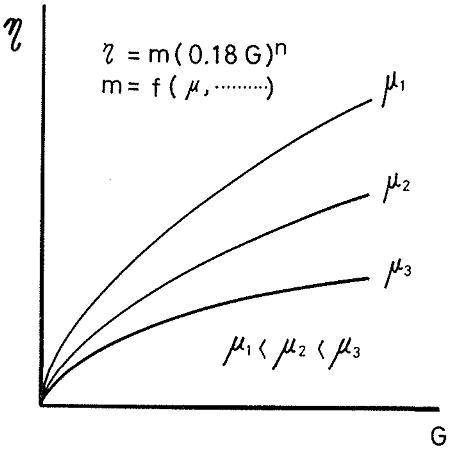

Fig. 13 Influence of ratio of air volume in clothing μ on η.

becomes sufficiently small, η gradually approaches a constant value. When n is zero in Fig. 12 η may be exressed by η=constant line, and a coincidence with Nishi's F_{pcl} which will be described later was seen.

Further regarding the influence of ratio of air volume in clothing μ on η, as shown in Fig. 13 a considerable influence on η value was seen.

5.3 The relationship of Woodcock's permeability index (i_m) and η

In 1962, as a means of expressing moisture permeation of clothing, Woodcock proposed a moisture permeability index (i_m)[7].

This index together with the equation expressing dry and wet heat release from the human body, is defined by the following equation.

$$H=\frac{3.09}{I_a+I_{clo}}\{(T_s-T_a)+i_m s(P_s-P_a)\} \tag{19}$$

where s : modificd Lewis relation factor [deg (°F)/mmHg]
T_s : cylinder surface temperature [°F]
T_a : air temperature [°F]
P_s : vapor pressure of cylinder surface [mmHg]
P_a : vapor pressure of air [mmHg]
I_a : clo value of heat transfer resistance [−]
I_{clo} : clo value of clothing [−]
i_m : Woodcock's permeability index [−]

Woodcock used a cylinder with a diameter of 6 inches and a height of 6 inches. The surface was maintained at a constant wet state, and after covering this with cloth, T_s, T_a, P_s and P_a were measured under a steady state. In addition using equation (19) with $H=0$, he obtained i_m values and empirical conclusions.

The relation between Woodcock's index i_m and clo value was derived from equations (12), (13), and (19).

$$i_m=\frac{5.56}{3.09}\left(\frac{0.18G+\frac{1}{\alpha_r+\alpha_c}}{0.238G^{9/8}+\frac{1}{\alpha_c}}\right) \tag{20}$$

5.4 The relationship between Nishi's permeation efficiency factor and η

As a unit for expressing moisture permeation, Nishi et al. set forth a permeation efficiency factor expressed as F_{pcl}.[1] They applied the analogy of heat transfar and mass transfer, and lead forth F_{pcl} theoretically. In order to show the feasiblity thereof they carried out sublimation experiments using naphthalene. F_{pcl} takes the value of $0 \leqq F_{pcl} \leqq 1$ because of air movement and clothing. The proposed equation and a schematic diagram are expressed collectively in Fig. 14.

$$F_{pcl}=\frac{1}{1+0.143 I_{clo} h_c} \qquad (21)$$

$$=\frac{1}{1+0.166 G\alpha_c} \qquad (22)$$

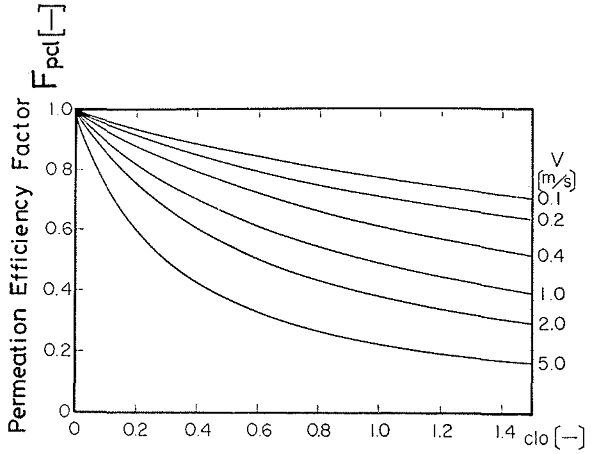

Fig. 14 Permeation Efficiency Factor F_{pcl}.

where F_{pcl}: permeation efficiency factor [−]
h_c: convective heat transfer coefficient [watt/m^2 deg (°C)]
0.143 : constant [m^2 deg (°C)/watt]
0.166 : constant [m^{2}h deg (°C)/kcal].

When F_{pcl} of equation (22) is rewritten in accordance with their original definition in the form of resistive components, the following relation is obtained.

$$0.166G+\frac{1}{\alpha_c}=0.18\times 0.923G+\frac{1}{\alpha_c} \qquad (23)$$

When the authors' basic formula (3) and equation (23) are compared, η shows a constant value of $\eta=0.923$ and the relationship is expressed as Fig. 15. The difference of two lines in Fig. 15 results from which l_g is assumed to be in linear proportion to clo or not to be.

In contrast when η is expressed in F_{pcl} form equation (24) is obtained and we have Fig. 16.

$$F'_{pcl}=\frac{1}{1+0.238G^{9/8}\alpha_c} \qquad (24)$$

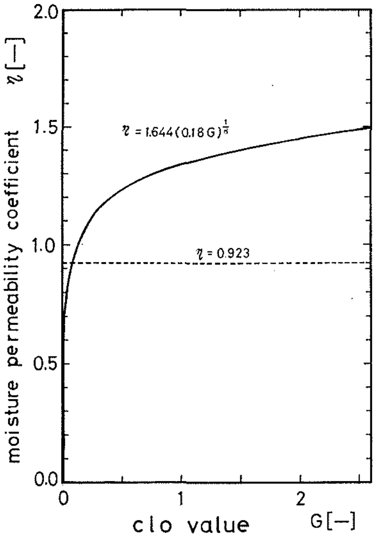

Fig. 15 F_{pcl} expressed in η form.

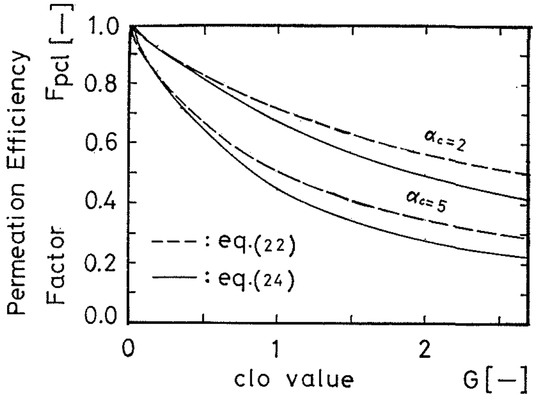

Fig. 16 η expressed in F_{pcl} form.

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