Influence of Heat Loss by Clothing Ventilation on Thermal Sensation

Tohru MOCHIDA*

(Received June 24, 1977)

Abstract

Wearing garments gives rise to so-called "clothing Ventilation" and the heat loss due to it may be expected.

A calculating formula for this heat loss is proposed, based on an idealized model of the actual complicated clothed state.

Further, from the heat balance between man and his environment, a constant temperature sensation equation is derived, in which not only the heat loss by clothing ventilation, but also the dry and the wet heat losses from the body skin and respiration heat loss are all included.

Assuming a comfortable condition at light office work, and substituting the reasonable values for that into the parameters in the derived formula and equation, we obtain a result which indicates that the ventilation heat loss can not be neglected and the clothing ventilation does have a considerable influence on the thermal sensation.

1. Introduction

We live dressed in garments for the greater part of our daily life. On one hand, garments have their social purposes, on the other hand, it plays an important physiologically role of regulating body temperature smoothly by making a mild thermal environment around the body.

From the point of view of heat transmission, the garment acts as a heat resistant material and also forms a resistance to moisture. Further, since a kind of space is formed between the skin and the clothes or between clothings themselves, it causes clothing ventilation, and heat loss by this ventilation may well take place.

Although the results of experiments on clothing ventlation itself are sometimes seen, there are very few reports about heat loss by clothing ventilation.

The author refers to a calculating method of the heat loss by clothing ventilation, by setting up an idealized model of the actual complicated state. Further, the effect of the ventilation heat loss on thermal sensation will be examined, based on a heat balance equation involving clothing ventilation heat loss in addition to heat losses by convection, radiation, perspiration, respiration and external mechanical work.

* Department of Sanitary Engineering, Faculty of Engineering, Hokkaido University, Sapporo, 060, Japan.

2. Basic Theory

The metabolic energy produced in the body is released into the environment via various pathways. As the main pathways in a steady state, heat losses by convection, radiation, perspiration, respiration and external mechanical work have been considered hitherto. But, since a kind of space between the skin and the outer surface of the garment is formed by wearing garments, so-called clothing ventilation occurs and the heat loss due to it will take place at the same time.

A thermal equilibrium between man and the environment is given by the following equation, when clothing ventilation is considered[1).

$$M=H_c+H_r+H_e+H_n+H_w+H_z \tag{1}$$

where, M: net rate of metabolic energy, Kcal/m²h

H_c: heat loss by convection, Kcal/m²h

H_r: heat loss by radiation, Kcal/m²h

H_e: heat loss by perspiration, Kcal/m²h

H_n: heat loss by respiration, Kcal/m²h

H_w: heat loss by external mechanical work, Kcal/m²h

H_z: heat loss by clothing ventilation, Kcal/m²h

In order to calculate the heat loss by clothing ventilation, the author will treat the clothed state as follows.

Owing to fibers and air in the garment, an actual clothed state is so complicated that the assumption of an idealized model in Fig. 1 can not be avoided. According to the thinking of Fig. 1 in which clothes are assumed to be thermally homogeneous, a concentrated ventilating channel is imagined at an arbitrary position in I clo and it may be assumed that air volume of ventilation Z with the air temperature T and the humidity ratio X passes through the channel. To continue

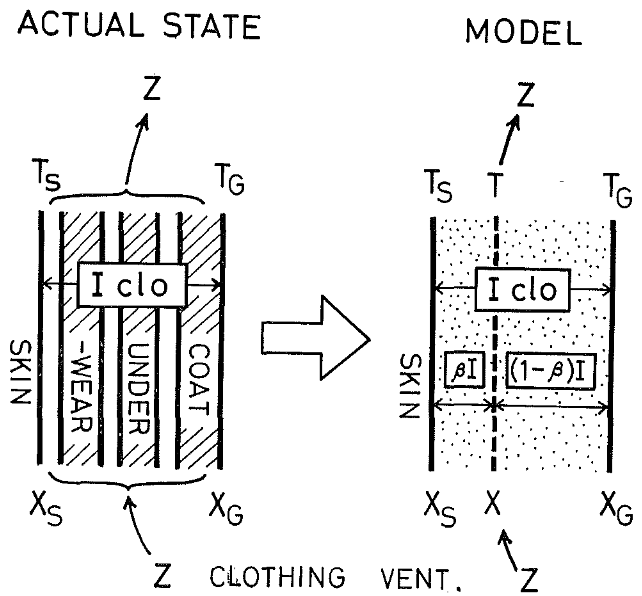

Fig. 1 Model of clothed state (T_s-X_s model)

this treatise, it is necessary to define the general theme; only the flow of air parallel to the skin or the garment in the clothed space is regarded as clothing ventilation in the present study.

With these assumptions, the following equation of heat loss by clothing ventilation is derived by referring to Fig. 1.

$$H_z = M - H_c - H_r - H_e - H_n - H_w$$
$$= \frac{Z}{A}\{c(T - T_a) + \rho L(X - X_a)\} \quad (2)$$

where, Z: air volume of clothing ventilation, m^3/h

A: man's DuBois area (assumed to be equal to the areas of convection, radiation and evaporation heat transfer respectively and moreover the increase of the surface area by wearing the garment is neglected as the effect is small in this paper), m^2

c: heat capacity, $Kcal/m^3{}^\circ C$

ρ: density, kg/m^3

L: latent heat, Kcal/g

T_a: temperature of ambient air, °C

T: temperature of air passing through a ventilating channel imagined in the clothed space, °C

X_a: humidity ratio of ambient air, g/kg

X: humidity ratio of air passing through a ventilating channel imagined in the clothed space, g/kg

On the other hand, at a uniform environment where air temperature is equal to the radiant temperature, neglecting convection in the clothed space, we can express the heat flux penetrating the clothed space to the outer environment by the following equations with clo unit.

$$\frac{T_s - T}{0.18I\beta} = K(T - T_a) \quad (3)$$

$$\frac{X_s - X}{0.166I\beta} = N(X - X_a) \quad (4)$$

where,

$$K \equiv \frac{1}{0.18I(1-\beta) + \frac{1}{h_c + h_r}} + \frac{cZ}{A}$$

$$N \equiv \frac{1}{0.166I(1-\beta) + \frac{1}{h_c}} + \frac{\rho LZ}{\kappa A}$$

T_s: skin surface temperature, °C

X_s: humidity ratio of skin, g/kg

I: clo unit (1 clo = 0.18 $m^2h^\circ C/Kcal$), N. D.

β: coefficient which relates to an imaginary ventilating channel (see Fig. 1), N. D.

h_c: man's convective heat transfer coefficient, $Kcal/m^2h^\circ C$

h_r: man's linear radiation exchange coefficient, $Kcal/m^2h^\circ C$

κ: modified Lewis relation, °C/(g/kg)

By eliminating the air temperature T and the humidity ratio X in an imaginary ventilating channel from Eqs. (2), (3) and (4), we can derive an equation for the heat loss H_Z by clothing ventilation as;

$$H_Z=\frac{Z}{A}\left\{\frac{c}{1+0.18I\beta K}(T_s-T_a)+\frac{\rho L}{1+0.166I\beta N}(X_s-X_a)\right\} \tag{5}$$

At the moment, however, it is difficult to obtain concrete values of H_Z, since we can not estimate a humidity ratio X_s at the skin which is generally unsaturated.

3. Thermal Sensation Index Considering Heat Loss by Ventilation under the Garment

3-1. Heat losses by convection and radiation

Along with the clothing model of Fig. 1, another model of a clothed state represented with the assumption of saturated humidity at skin surface is shown in Fig. 2.

Based on the model of Fig. 2, convective and radiative heat loss in a uniform environment is given by the following equation.

$$H_c+H_r=\frac{1}{0.18I(1-\beta)+\dfrac{1}{h_c+h_r}}(T-T_a) \tag{6}$$

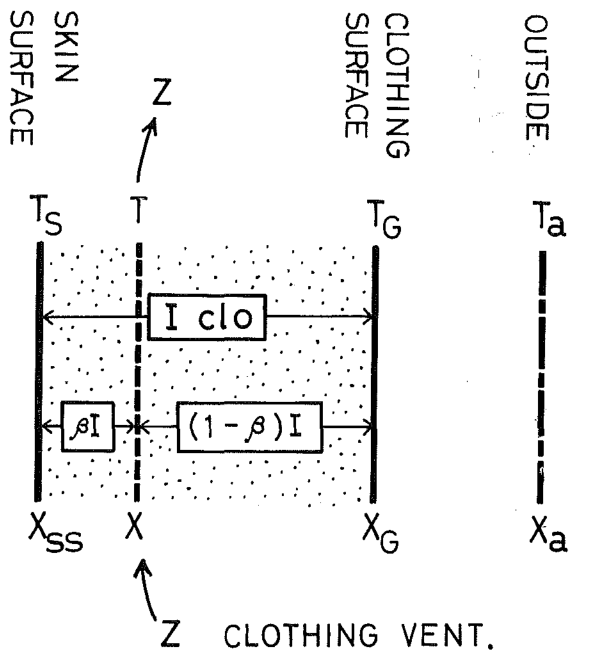

Fig. 2 Model of clothed state (T_S-X_{SS} model)

3-2. Heat loss by perspiration

Heat loss by perspiration for a nude man is expressed by Eq. (7), by use of the wettedness due to Gagge et al.[2)]

$$H_e=\kappa h_c(X_{ss}-X_a)W \tag{7}$$

$$=\frac{\kappa}{\frac{1}{h_c}}(X_{ss}-X_a)W \tag{8}$$

where, X_{ss} : saturated humidity ratio at skin temperature T_s, g/kg

W : wettedness by Gagge et al., N. D.

Further, heat loss by perspiration for a clothed man is given by the following equation using the permeation efficiency factor f_{pcl} proposed by Nishi et al.[3]

$$f_{pcl}=\frac{1}{0.166Ih_c+1} \tag{9}$$

$$H_e=f_{pcl}\kappa h_c(X_{ss}-X_a)W \tag{10}$$

where, f_{pcl} : permeation efficiency factor by Nishi et al., N. D.

Substitution of Eq. (9) into Eq. (10) and rearrangement gives Eq. (11) which is similar to Eq. (8).

$$H_e=\frac{\kappa}{0.166I+\frac{1}{h_c}}(X_{ss}-X_a)W \tag{11}$$

In Eq. (11), the humidity difference $(X_{ss}-X_a)$ represents a driving force and the term $(0.166I+1/h_c)$ shows a series resistance from the skin surface under the garment to the outer environment.

If the same thinking regarding the part of resistance is applied to Fig. 2, perspiration heat loss can be written formally by the following equation in a similar manner to Eq. (11).

$$H_e=\frac{\kappa}{0.166I(1-\beta)+\frac{1}{h_c}}(X-X_a)W \tag{12}$$

3-3. Heat loss by respiration

In order to calculate respiration heat loss, the following expression proposed by Fanger[4] is used in the present study.

$$H_n=M(0.148-0.00276X_a-0.0014T_a) \tag{13}$$

3-4. Heat loss by clothing ventilation

Against the clothed state model shown in Fig. 2, we assume that a concentrated channel for ventilating exists at an arbitrary position in the clothed space between the skin and the outer surface of the garment and that air volume of clothing ventilation Z with the temperature T and the humidity ratio X passes through this channel. As described previously, only the flow of air parallel to skin or the garment in the clothed space is regarded as clothing ventilation, and the ventilating flow of air normal to the garment is neglected in this paper.

From the above assumptions, heat loss by clothing ventilation is given by the following equation for the case of the model shown in Fig. 2.

$$H_z=\frac{Z}{A}\{c(T-T_a)+\rho L(X-X_a)\} \tag{14}$$

The expression in which the imaginary temperature T and humidity X are eliminated from Eq. (14) will be described later.

3-5. Thermal equilibrium between the human body and the environment

We obtain a heat balance equation between man and his environment in a steady state by combination of Eqs. (1), (6), (12), (13) and (14).

$$M=\frac{1}{0.18I(1-\beta)+\frac{1}{h_c+h_r}}(T-T_a)+\frac{\kappa}{0.166I(1-\beta)+\frac{1}{h_c}}(X-X_a)W$$
$$+\frac{Z}{A}\{c(T-T_a)+\rho L(X-X_a)\}+M(0.148-0.00276X_a-0.0014T_a)+\mu M \tag{15}$$

where, μ : external mechanical efficiency, N. D.[4)]

On the other hand, Eqs. (16) and (17) hold with respect to the flow of heat and moisture between the skin and the outer environment.

$$\frac{T_s-T}{0.18I\beta}=P(T-T_a) \tag{16}$$

$$\frac{X_{ss}-X}{0.166I\beta}=R(X-X_a) \tag{17}$$

where,

$$P\equiv\frac{1}{0.18I(1-\beta)+\frac{1}{h_c+h_r}}+\frac{cZ}{A}$$

$$R\equiv\frac{1}{0.166I(1-\beta)+\frac{1}{h_c}}+\frac{\rho LZ}{\kappa WA}$$

If the imaginary temperature T and humidity ratio X are eliminated from Eqs. (15), (16) and (17), the following equation, for the constant skin temperature (=constant wettedness) line, results.

$$\xi_z X_a=-\omega_z T_a+\zeta_z \tag{18}$$

where,

$$\xi_z\equiv\frac{\kappa WR}{0.166I\beta R+1}+0.00276M$$

$$\omega_z\equiv\frac{P}{0.18I\beta P+1}+0.0014M$$

$$\zeta_z\equiv\frac{PT_s}{0.18I\beta P+1}+\frac{\kappa WRX_{ss}}{0.166I\beta R+1}+M(\mu+0.143-1)$$

Finally, the calculating equation (14) for clothing ventilation heat loss is transformed into Eq. (14)′ by elimination of the imaginary temperature T and humidity ratio X.

$$H_z=\frac{Z}{A}\left\{\frac{c(T_s-T_a)}{0.18I\beta P+1}+\frac{\rho L(X_{ss}-X_a)}{0.166I\beta R+1}\right\} \tag{14'}$$

3-6. Constant skin temperature line considering clothing ventilation

We may draw the constant skin temperature lines taking the clothing ventilation into consideration on the psychrometric chart by substituting concrete values concerned into Eq. (18).

Due to insufficient data regarding air volume of clothing ventilation, as a temporary standard, let us substitute experimental data[5)] in the past $Z=0.5\sim1.0$ m^3/h into Eq. (18) and draw constant skin temperature lines.

We obtain constant skin temperature lines by substituting the following values into Eq. (18), which are assumed for a normally clothed man working in an office at comfort.

$M = 55$ Kcal/m²h

$I = 1$ clo

$A = 1.6$ m²

$T_s = 33.5$°C

$X_{ss} = 33.5$ g/kg

$W = 0.06$ N. D.[2]

$\mu = 0$ N. D.[4]

$V = 0.1$ m/s ($h_c = 2.95$ Kcal/m²h°C)*

$h_r = 4.8$ Kcal/m²h°C[6]

$\kappa = 2.23$°C/(g/kg)

$c = 0.3$ Kcal/m³°C

$\rho = 1.2$ kg/m³

$L = 0.58$ Kcal/g

$\beta = 0.5$ N. D.

$Z = 0.5$ m³/h[5]

The constant skin temperature line for the case of $Z = 0$ was drawn by Eq. (20) rearranged from the heat balance expression (19), which ignores clothing ventilation.

$$M = H_c + H_r + H_e + H_n + H_w = \frac{1}{0.18I + \frac{1}{h_c + h_r}}(T_s - T_a)$$

$$+ \frac{\kappa}{0.166I + \frac{1}{h_c}}(X_{ss} - X_a)W + M(0.148 - 0.00276X_a - 0.0014T_a) + \mu M \tag{19}$$

$$\xi_0 X_a = -\omega_0 T_a + \zeta_0 \tag{20}$$

where,

$$\xi_0 \equiv \frac{\kappa W}{0.166I + \frac{1}{h_c}} + 0.00276M$$

$$\omega_0 \equiv \frac{1}{0.18I + \frac{1}{h_c + h_r}} + 0.0014M$$

$$\zeta_0 \equiv \frac{T_s}{0.18I + \frac{1}{h_c + h_r}} + \frac{\kappa W X_{ss}}{0.166I + \frac{1}{h_c}} + M(\mu + 0.148 - 1)$$

And, in a day to day living area, the general relation between Eqs. (18) and (20) is shown as Fig. 4. The relations of the absolute value of the gradient and the point on the vertical axis ($T_a = 0$°C) between Eqs. (18) and (20) are as follows.

* The effect of the garment worn is neglected as small and the equation $h_c = {}^3\sqrt{270V^2 + 23}$ of convective heat transfer coefficient for the human body[6] is used in the present paper.

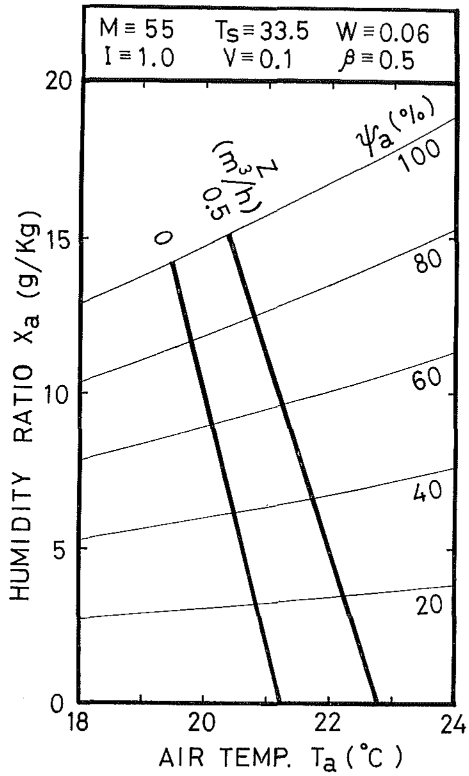

Fig. 3 Comparison of constant skin temperature lines (clothing ventilation $Z \equiv 0.5\ m^3/h$ and $Z \equiv 0$)

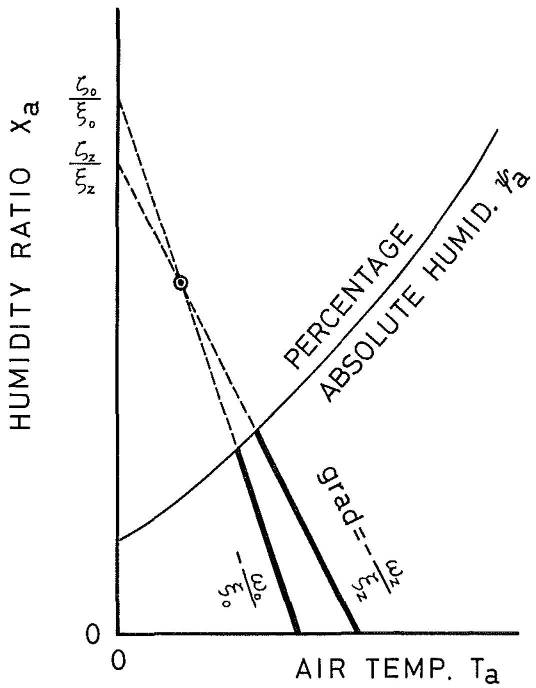

Fig. 4 Relation of Eq. (18) and Eq. (20)

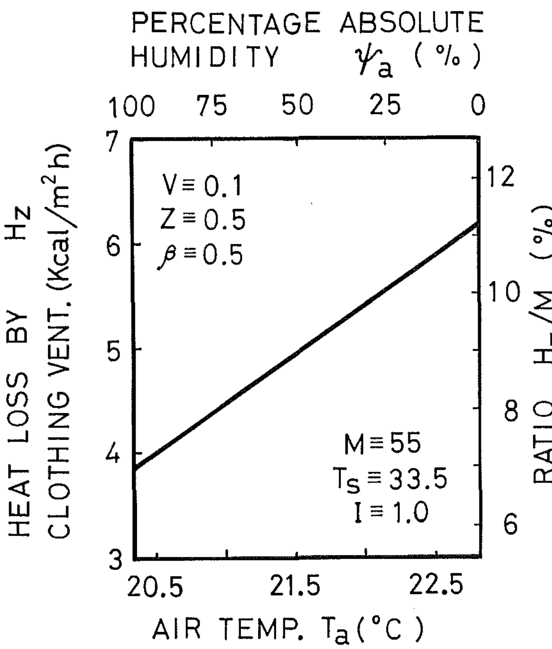

Fig. 5 Clothing ventilation heat loss and its ratio to total heat loss (low air movement)

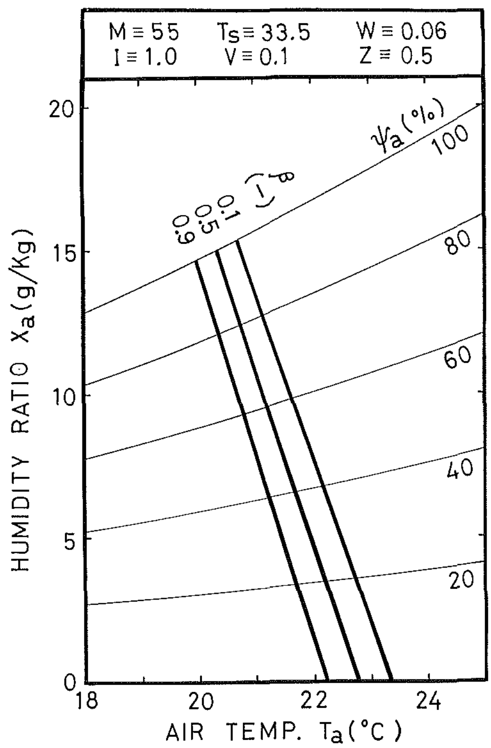

Fig. 6 Effect of β on constant skin temperature line

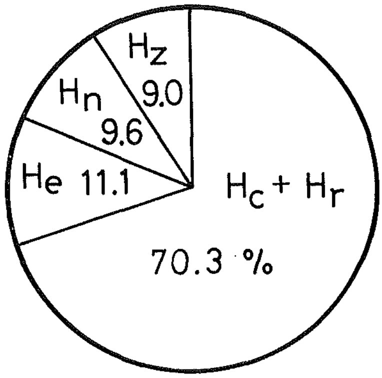

Fig. 7 Percentage of each heat loss

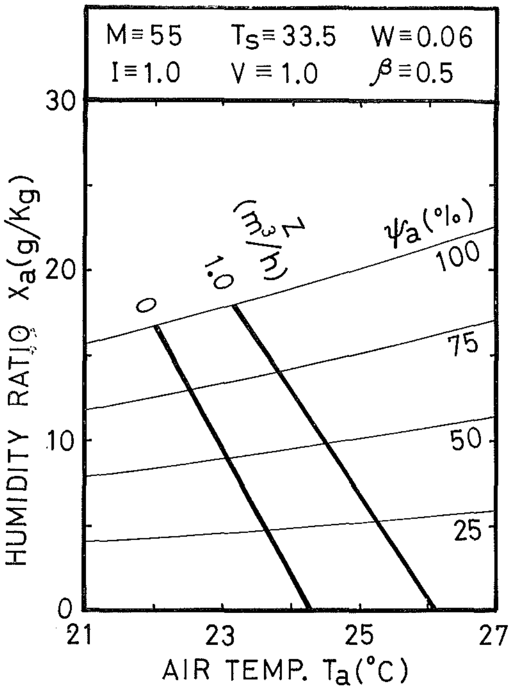

Fig. 8 Comparison of constant skin temperature lines (clothing ventilation $Z\equiv 1.0\,m^3/h$ and $Z\equiv 0$)

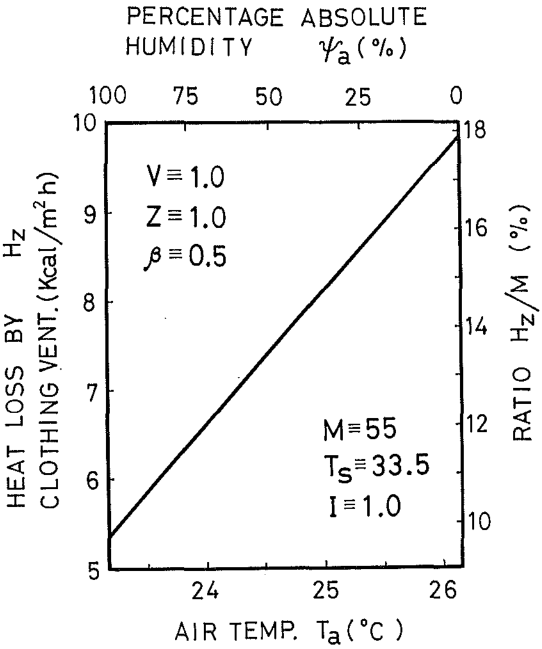

Fig. 9 Clothing ventilation heat loss and its ratio to total heat loss (high air movement)

The absolute value of the gradient: $\left|\frac{\omega_0}{\xi_0}\right| \geqq \left|\frac{\omega_z}{\xi_z}\right|$

The point on the vertical axis: $\frac{\zeta_0}{\xi_0} \geqq \frac{\zeta_z}{\xi_z}$

A difference of about 1.5°C converted into air temperature can be read between two lines in Fig. 3. And, we may also conclude from the calculated results of Fig. 5 that the ratio of heat loss by clothing ventilation to total heat loss is approximately 10% and that heat loss by the ventilation is almost equal to that by respiration and that it can not be neglected as small.

Since the coefficient β representing the position of an imaginary ventilating channel within the clothed space can take a value between 0 and 1.0, the effect of β on constant skin temperature lines is examined in Fig. 6. From the result of Fig. 6, the average value $\beta=0.5$ will be used in the calculations hereafter. Further, on the 50% humidity line of constant skin temperature line involving clothing ventilation, percentage of each released heat quantity is compared in Fig. 7. As is seen in Fig. 7, the sum of the heat loss by convection and radiation is in proportion to 70% of total heat loss and the sum of heat loss by perspiration and respiration is in proportion to 20% of the total.

Eq. (14)′ also expresses that heat loss by clothing ventilation increases as the air volume of the ventilation increases. This was examined in Fig. 8. Fig. 8 was drawn by using the values at high air movement in Eq. (18). The same values described previously are substituted except for $Z=1.0\ m^3/h$[5] and $h_c=6.64$ $Kcal/m^2h°C$ ($V=1.0$ m/s)[6].

As a result, the effect by clothing ventilation heat loss is remarkable as was the case in Fig. 3 and the difference of about 2°C in air temperature is seen between the lines of $Z=1\ m^3/h$ and $Z=0$. Further, the proportion of ventilation heat loss to the total becomes larger as the humidity of the environment becomes lower and Fig. 9 shows that heat loss by clothing ventilation is more than 17% when the humidity is close to 0%.

4. Conclusions

In general, heat losses by convection, radiation, perspiration, respiration and external mechanical work have been mainly considered as the released heat which is transferred from the human body to the environment in a steady state. But, since garments cause the so-called clothing ventilation, heat loss by it may be expected.

The author derived a calculating formula of clothing ventilation heat loss. The analysis was based on a following simple clothed model with a concentrated ventilating channel. Since the actual clothed state is rather complicated owing to fibers and air, the clothed space between the skin and the outer surface of the garment is assumed to be thermally homogeneous and also an imaginary ventilating channel may be assumed to exist in it.

Using the model and the formula derived, calculation of the heat loss by clothing ventilation was attempted, for the case when a person is engaged in the duties in a comfortable office room. As a result, the heat loss was approximately 4~6 $Kcal/m^2h$ and the ratio of this heat loss to the total was about 7~11%, which was almost equal to the heat loss by respiration. Further, the ratio under the high air motion amounted to about 20%. From the facts described above, it became clear that heat loss by clothing ventilation may not be so little as to be neglected and that clothing ventilation had a great influence on thermal sensation.

As subjects for a future study we may attempt to obtain accurate experimental data regarding clothing ventilation by using man or a manikin and also attempts may be made to elucidate further the detailed mechanism for clothing ventilation in an actual clothed state.

References

1) T. Mochida: Examination of thermal sensation index considering clothing ventilation, SHASE annual meeting, 1975, p. 217.

2) A. P. Gagge, J. A. J. Stolwijk and Y. Nishi: An effective temperature scale based on a simple model of human physiological regulatory response, ASHRAE Trans., Vol. 77, Part I, 1975, p. 247.

3) Y. Nishi and A. P. Gagge: Moisture permeation of clothing—A factor governing thermal equilibrium and comfort, ASHRAE Trans., Vol. 76, Part I, 1970, p. 137.

4) P. O. Fanger: Calculation of thermal comfort, introduction of a basic comfort equation, ASHRAE Trans., Vol. 73, PartII, 1967, p. 1.

5) H. Shoji: Ifuku no eiseigaku (Hygiene of clothing, in Japanese), Koseikan, 1969. p. 49.

6) T. Mochida: Convective and radiative heat transfer coefficients for the human body, Bulletin of the Faculty of Engineering, Hokkaido University, No. 84. 1977, p. 1.