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Title	Convective and Radiative Heat Transfer Coefficients for a Clothed Man
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Citation	北海道大學工學部研究報告, 94, 1-9
Issue Date	1979-06-29
Doc URL	https://hdl.handle.net/2115/41566
Type	departmental bulletin paper
File Information	94_1-10.pdf

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北海道大学工学部研究報告
第94号（昭和54年）

Bulletin of the Faculty of Engineering,
Hokkaido University, No. 94 (1979)

Convective and Radiative Heat Transfer Coefficients for a Clothed Man

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(Received December 28, 1978)

Abstract

The convective and the radiative heat transfer coefficients for the human body have been proposed by physiologists and biological engineers. But considerable differences are seen among these obtained values and proposed equations, which were obtained by experiments using human subjects or derived by theoretical analyses. The main reason appears to arise from the fact that a human subject is a thermal body with a complicated form and that it is quite difficult to obtain "precise" data from experiments using the human body.

The convective and the radiative heat transfer coefficients for an unclothed man were previously derived by the author from an engineering method based on the heat transfer theory taking into consideration the physiological properties of the human body.

The present paper deals with the convection and the radiation coefficients for a clothed man and the concrete values, a convective heat transfer coefficient for a clothed man $h_c=\sqrt[3]{270\,V^2+23}$ and a linear radiation exchange coefficient $h_r=5$ Kcal/m²h°C, which are extended for those of an unclothed man derived in the previous study, are proposed.

1. Introduction

Convective, radiative and evaporative heat transfer coefficients are three major parameters in the study of heat transfer of the human body. This paper deals with the convective and the radiative coefficients since the evaporative one can be expressed in the form of the product of the convective coefficient and Rewis constant.

The convective heat transfer coefficient of human body has been proposed by physiologists and biological engineers since more than half a century ago. However the actual values and formulas proposed, which were obtained by experiments using human subjects or derived from theoretical analyses, are considerably different from each other, although the conditions of experiments such as clothing, posture, temperature, humidity, air movement and so forth, were more or less different in each case.

For instance, as one of the major causes which brought about the differences, let us imagine the measurement of skin temperature which is fundamental when the value of heat transfer coefficients are calculated and determined from experimental data obtained. As to the section of the site on the skin, and also the difference among the mean skin temperatures caused by various averaging methods,

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accuracy of measuring apparatus and so forth have a great influence on measurement and calculation of skin temperature. Therefore a difference among the convective heat transfer coefficients obtained would naturally arise if they are to be calculated mainly from the experimental data.

The author examined theoretically the convective heat transfer coefficient for an unclothed man from an engineering point of view taking into consideration the physiological properties of the human body and a proposal was made of an actual value and an equation. Extending the results obtained previously, their values for a clothed person will be discussed in the present study.

The radiation heat exchange can be exactly calculated by the difference of the fourth power of the absolute temperature between the surfaces of a man and his surrounding walls, but we usually express the radiation heat exchange with the mere surface temperature difference, using linear radiation exchange coefficient defined by limiting the temperature range. The question would be that how the radiation coefficient should be defined and which value should be substituted as the actual values of emissivity and the temperature factor. Although there are various expressions about the radiation coefficient, the expression obtained by extending and developing Gebhart's absorption factor which considers the multiple radiation is used in this paper. The new radiative heat transfer coefficient is expressed in the form of a product of Stefan-Boltzmann constant, temperature factor and the emissivity of the human surface — skin or clothing — and does not include the emissivity of the surrounding wall surface which the previous expression heretofore contains. In the present study, the influence of clothing on the radiation heat transfer coefficient is especially discussed and an actual value is proposed.

2. Nomenclature

H: heat loss by convection and radiation, Kcal/m²h
Q_r: heat released by radiation, Kcal/h
h_c: man's convective heat transfer coefficient, Kcal/m²h°C
h_r: man's linear radiation exchange coefficient derived by extending the absorption factor method and applying it to the space between man and his surrounding walls, Kcal/m²h°C
α_r: man's linear radiation exchange coefficient derived by restriction to only direct radiation exchange, Kcal/m²h°C
I: clo unit (1 clo=0.18 m²h°C/Kcal), N. D.
ε_g: emissivity of the human surface, N. D.
ε_i: emissivity of the wall i, N. D.
σ: Stefan-Boltzmann constant, Kcal/m²h°K⁴
φ_{gi}: angle factor from the human body g to the wall i, N. D.
b_{gi}: absorption factor between the human body g and the wall i, N. D.
V: air movement, m/s
l_g: thickness of clothing, m
A_r: effective surface area which relates to radiant heat exchange, m²
T_s: mean skin temperature at comfort condition, °C
T_g: outer surface temperature of clothing, °C
T_i: wall temperature, °C
k: temperature factor of radiation heat exchange=$[(T_g+273)^2+(T_i+273)^2]$

$\times[(T_g+273)+(T_i+273)]$, °K³

Nu: Nusselt number (mixed=natural and forced), N. D.

Nu_{for}: Nusselt number (forced), N. D.

Gr: Grashof number, N. D.

Re: Reynolds number, N. D.

3. Convective heat transfer coefficient for a clothed man

3-1. Convective heat transfer coefficient for an unclothed man

The author proposed previously an equation of convective heat transfer coefficient for an unclothed person mainly by theoretical analysis based on heat transfer theory[1].

The outline is as follows.

Since the form of a human body is so complicated that it is difficult to determine the exact convective heat transfer coefficient, a cylinder model dividing the entire body into several parts will be taken as one of the methods for determination. The human body will be considered to be an assembly of several cylinder segments. The cylinder model of a human body by Parker et al[2] was consulted in the persent paper and the whole body was divided into six parts — head (including neck), trunk, upper arms, forearms (with fingers), thighs and legs — and each typical diameter of those cylinders and skin areas was used in round numbers with reference to the numbers by Parker et al and are listed in Table 1[1]. Further, using Hilpert's dimensionless equation for forced convective heat transmission (Table 2)[3] and Oosthuizen-Madan's dimensioless equation (2) for mixed (natural and forced)[4], local convective heat transfer coefficients according to Table 1 were calculated. As an approximate equation which gives the mean convection coefficient for the human body, Eq (1) taking into consideration natural convection especially in low velocity regions was proposed.

$$h_c=\sqrt[3]{270\,V^2+23}\ (0.1\leqq V\leqq 3.0) \tag{1}$$

$$\frac{Nu}{Nu_{for}}=1+0.18\left(\frac{Gr}{Re^2}\right)-0.011\left(\frac{Gr}{Re^2}\right)^2 \tag{2}$$

Table 1. Typical diameters and skin areas of body segments[1]

	Head	Trunk	Upper arms	Forearms	Thighs	Legs
Diameter [m]	0.2	0.3	0.1	0.1	0.2	0.1
Skin area [m²]	0.2	0.6	0.1	0.2	0.4	0.3

Table 2. Hilpert's dimensionless equation[3] (forced convective heat transmission)

$Nu_{for}=mRe^n$

(Prandtl number $Pr=0.72$)

Re	m	n
40～4000	0.615	0.466
4000～40000	0.174	0.618

3-2. Diameter of a clothed man-equivalent thermal cylinder

The diameter of 18 cm was theoretically obtained as that of a thermal cylinder

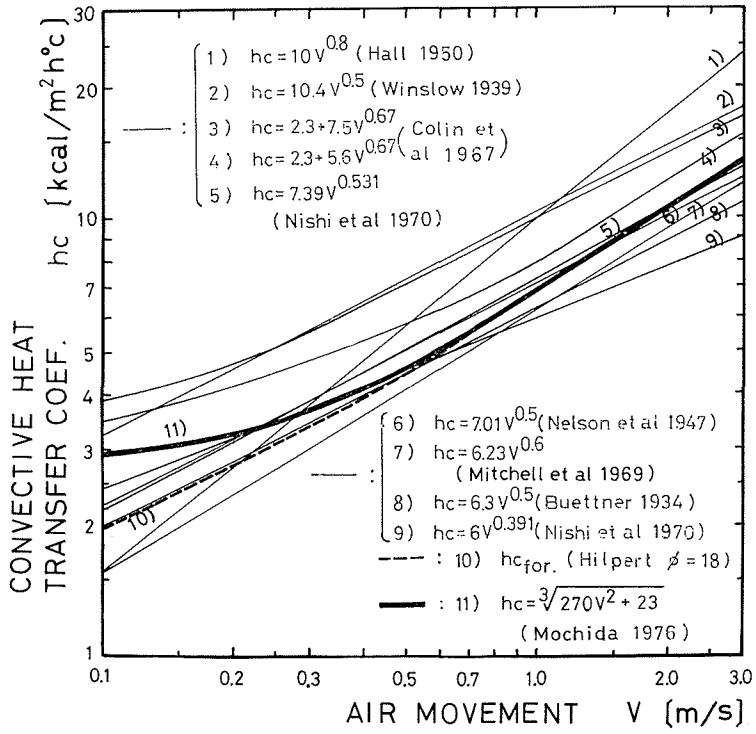

Fig. 1 Comparison of convective heat transfer coefficients for the human body[1]

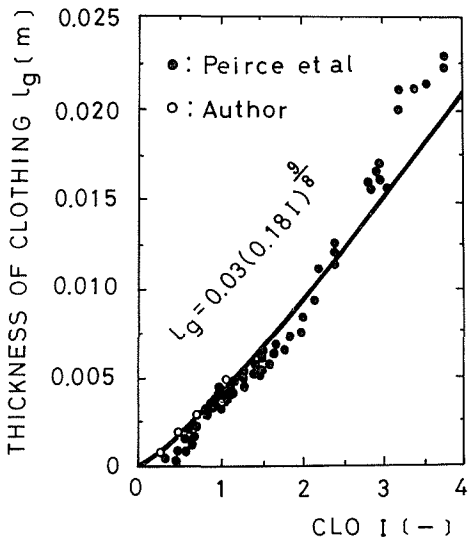

Fig. 2 Relation between thickness of clothing and clo value[6]

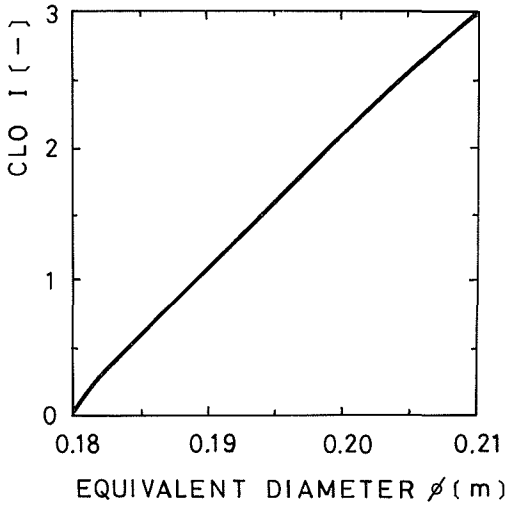

Fig. 3 Relation between clo value and diameter of a "clothed" cylinder

equivalent to human when he was unclothed in the process in which Eq. (1) was derived[1].

Let us imagine a clothed man-equivalent thermal cylinder which wears garment on the 18 cm diameter thermal cylinder[5]. And we will consider that the equivalent diameter grows thick as clothings are worn one over the other.

The relation between clo value and the thickness of clothes is given by the following equation[6].

$$l_g = 0.03(0.18\,I)^{9/8} \tag{3}$$

By putting the clothing given by Eq. (3) on the 18 cm diameter cylinder equivalent to an unclothed man, the relation between the diameter of a clothed man-equivalent thermal cylinder and clo value is shown in Fig. 3.

3·3. Convective heat transfer coefficient for a clothed man

On the basis of the clothed man-equivalent cylinder, convection coefficient for a clothed man is discussed as follows by using Oosthuizen-Madan's dimensionless equation for mixed heat transfer in the same way as that carried out in unclothed conditions.

Since the thickness of clothes changes the comfortable air temperature, the standard values of which corresponding to each condition are applied as the property values of matter consisting of dimensionless numbers Nu, Nu_{for}, Gr and Re in Eq. (2). Taking into consideration the condition when clo value was defined — 1 met ($H = 50 \times 3/4$ Kcal/m²h), comfortable air temperature 21°C and the skin temperature 33°C, in order to calculate Grashof number Gr, the standard temperature difference between the outer surface of clothing and the environment is first set on the basis of the difference between the clothing surface temperature 26.3°C obtained from Eq. (4) and the air temperature 21°C.

$$H = \frac{T_s - T_g}{0.18\,I} \tag{4}$$

Further, when clothing condition is not 1 clo, we are obliged to substitute the temperature difference 5°C, since we have no exact actual data about comfortable air temperature corresponding to each clothing condition. Although comfortable air temperature rises as air movement increases even if the metabolism and clothing condition do not change, it is enough to pay attention to only forced convection as the Reynolds number increases and the temperature difference between clothing surface and ambient air decreases. Moreover, since kinematic viscosity and thermal conductivity are hardly influenced by humidity[7], those of dry air[8] to the mean value of clothing surface temperature and air temperature in each clothing condition are substituted and Nusselt number Nu_{for} for forced

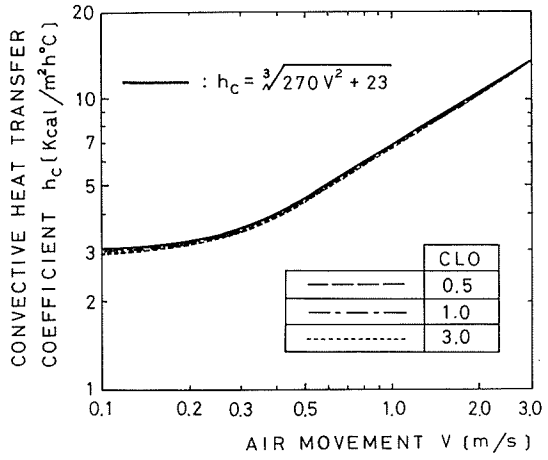

Fig. 4 Convective heat transfer coefficient for a clothed man

convection is calculated from Hilpert's dimensionless equation. In the present paper, a cylinder is regarded as a representative model of the human body, although it goes without saying that posture exerts a great influence on convective heat transfer coefficient.

The property of matter derived above are substituted into Eq. (2) and convective heat transfer coefficient for a clothed man are calculated and shown in Fig. 4.

Fig. 4 shows that there is little difference between the convection coefficients for an unclothed man and those of a clothed one. The reason would be imagined to be the effect of offset — an increment of the second term of the right side in Eq. (2) is almost equal to that of third term in spite of the change of values Gr and Re with the drop of the standard temperatures.

The above examination assures the usefulness of Eq. (1) which was previously derived as convective heat transfer coefficient for an unclothed as well as a clothed man in the comfortable region of everyday life.

4. Radiative heat transfer coefficient for a clothed man

4-1. Radiation heat exchange

The radiant energy balance is expressed as follows by only a direct radiation exchange if the multiple radiation is neglected.

$$Q_r=\alpha_r(T_g-\sum\varphi_{gi}T_i)A_r \tag{5}$$

The linear radiation heat transfer coefficient α_r as denoted in Eq. (5) is defined by the following equation in this case.

$$\alpha_r=\varepsilon_i\varepsilon_g\sigma k \tag{6}$$

Regarding the radiation heat exchange between the walls in a closed space, Gebhart proposed the absorption factor and expressed the results by using the fourth power of the absolute temperature. This is a calculation which takes into consideration the multiple radiation between walls not to speak of a direct radiation. The author extended this calculation and applied it to the space between the human body and the surrouuding walls[9]. The radiation heat exchange in this expression is written by the following equation and the linear radiation heat transfer coefficient h_r is given by Eq. (8).

$$Q_r=h_r(T_g-\sum b_{gi}T_i)A_r \tag{7}$$

$$h_r=\varepsilon_g\sigma k \tag{8}$$

According to the expression based on a direct radiation exchange, the emissivity of the wall is contained in the radiation coefficient α_r.

When h_r in Eq. (7) is compared with α_r in Eq. (5), h_r has only the emissivity of the human surface but α_r in itself includes both the emissivities of the walls and the human body surface. It follows that if each wall which encloses a human body is approximately a black body and moreover when all the emissivities of enclosing walls are equal or nearly equal, the difference between the values h_r and α_r may be almost negligible. However, it also follows that in the case of a special room having various walls with the great difference among their emissivities, another averaged emissivity $\bar{\varepsilon}_i$ must be employed. Moreover, $\sum b_{gi}T_i$ in Eq. (7) expresses a kind of mean radiant temperature and it is defined by a weighted mean of the temperatures of the surrounding surface with absorption

factors including angle factors. In order to differentiate the mean radiant temperature $\sum\varphi_{gi}T_i$ weighted with angle factors in Eq. (5) and to avoid confusion brought about by the difference in averaging, a new mean radiant temperature $\sum b_{gi}T_i$ will be refered to as "environmental radiant temperature". The characteristic features of the environmental radiant temperature weighted by the absorption factors are made not only for the geometric position but also for the emissivity of each wall surface in the absorption factor b_{gi}. Although we regard the human surface area which relates to radiation heat exchange as the whole body surface area for the present, when the values of the radiation area factor, which is usually said to be approximately 80% to the total surface area, and the ratios of decrease or increase by posture and clothing are obtained, the same rule will apply by multiplying Eq. (6) and Eq. (8) by those values.

4-2. Radiative heat transfer coefficient for a clothed man

In an ordinary room, as long waves are mainly involved, the skin of a human body and garment surface would have an emissivity close te that of a black body[10),11)]. In the present study we use emissivity ε_g of 0.95. We used the standard temperature difference between outer surface of clothing and ambient air in order to calculate Grashof number. Under the temperatures obtained from the standard temperature difference above, the radiation coefficient is calculated and shown in Fig. 5.

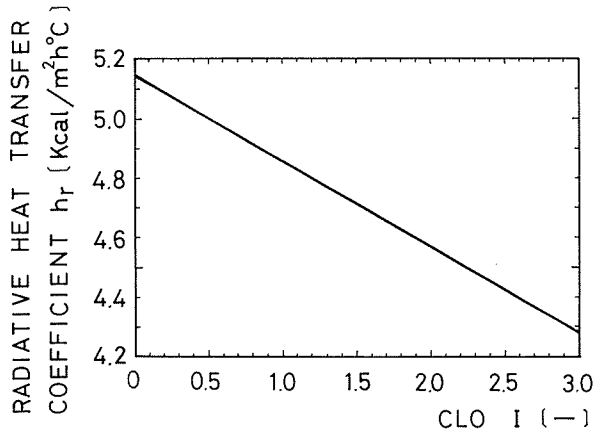

Fig. 5 Radiative heat transfer coefficient for a clothed man

Fig. 5 indicates that the radiative heat transfer coefficient h_r varies from 5.2 to 4.3 Kcal/m²h°C with 0 to 3 clo. Use of 5 Kcal/m²h°C as the actual radiation coefficient for the human body would practically be justified, since h_r to daily life clothing 0.5～1 clo is 5～4.8 Kcal/m²h°C.

5. Conclusions

Based on the heat transfer theory, the diameter of an unclothed man-equivalent thermal cylinder model was set at 18 cm. Moreover, by applying the dimensionless equations of heat transfer by Hilpert and by Oosthuizen-Madan to cylinder, Eq. (1) was theoretically derived as a formula which gives the mean convective heat transfer coefficient for an unclothed man and the formula takes into considerations natural and forced convection at the same time. Clothed condition

was stood for by putting clothes on the unclothed man-equivalent thermal cylinder and the diameter of a clothed cylinder was assumed to change according to the garment thickness corresponding to clo value. Further, the temperatures of outer surface of the garment and environment were fixed to the standard values at 1 clo-comfort condition and the properties of air at the mean temperature obtained were substituted into the Oosthuizen-Madam's dimensionless equation and the convective heat transfer coefficients to each clothing were calculated. As a result, we obtained the loci for a clothed man that have a strong resemblance to the convective heat transfer coefficient for an unclothed man. The main reason would be imagined to be the effect of offset — increase of the cylinder diameter by putting clothing and decrease of viscosity and thermal conductivity accompanying the drop of the standard comfort temperature with the increase of clo value. As a consequence of surveying from various aspects, the equation which calculates the convective heat transfer coefficient for an unclothed or a clothed man was proposed as follows.

Convective heat transfer coefficient for an unclothed and a clothed man;

$$h_c = \sqrt[3]{270\,V^2+23} \qquad \text{Kcal/m}^2\text{h°C}$$
$$(0.1 \leqq V \leqq 3.0\ \text{m/s})$$

Man's linear radiation exchange coefficient is generally expressed by the product of three or four items, that is, the temperature factor, Stefan-Boltzmann constant and the emissivities of the human body and the surrounding walls, but whether the coefficient has both emissivities or has only the emissivity of the human body surface depends on whether the multiple radiation exchange is taken into consideration or not. In the present study, the radiation coefficient which is expressed by the product of the emissivity of the human surface, the temperature factor and Stefan-Boltzmann constant was used. The expression was derived by linearizing the absorption factor by Gebhart and applying it to the space between a human body and its surroundings, and the coefficient includes no emissivity of the surrounding wall. With reference to the temperature regions where the convection coefficients were calculated, the radiation coefficients to clo values were calculated. The radiation coefficient has resulted in the values of 4.8 to 5.0 Kcal/m²h°C corresponding to 1.0 to 0.5 clo and it is justified to use practically the radiation coefficient $h_r = 5$ Kcal/m²h°C.

Radiation heat transfer coefficient for a clothed man;

$$h_r = \varepsilon_g \sigma k = 4.8 \sim 5.0 \qquad \text{Kcal/m}^2\text{h°C}$$
$$(1.0 \sim 0.5\ \text{clo})$$

References

1) T. Mochida; Convective and Radiative Heat Transfer Coefficients for the human body, Bulletin of the Faculty of Engineering, Hokkaido University, Japan, No. 84, 1977, pp. 1-11.
2) A. Parker, D. A. Ekberg, D. J. Withey et al; Atmosphere selection and control for manned space stations, General Electric Co., Missile and Space Div., Valley Forge, Pa., Presented at the International Symposium for Manned Space Stations in Munch, 1965 (Cited by Ningen-Kankyokei, Ningen To Gijutsusha, 1972, p. 185, Written in Japanese).
3) W. H. McAdams; Heat Transmission; McGraw-Hill, Kogakusha, 1962, p. 260.
4) P. H. Oosthuizen & S. Madan; Combined Convective Heat Transfer from Horizontal Cylinders in Air, ASME Trans., 1970. pp. 194-197.

5) T. Mochida; Convective Heat Transfer Coefficient for a clothed person, annual meeting at Architectural Institute of Japan, 1978, pp. 581–582.
6) T. Mochida & S. Yokoyama; Permeation Resistivity of Clothing, Bulletin of the Faculty of Engineering, Hokkaido University, Japan, No. 83, 1977, pp. 39–49.
7) K. Ibamoto & Y. Nishi; Thermal Sensation Analysis and its Application to Air-Conditioning, Bulletin of the Faculty of Engineering, Hokkaido University, Japan, No. 46, 1968, pp. 73–121.
8) The Japan society of mechanical engineers; Data book for heat transmission engineering (Dennetsu-kogaku-shiryo, Written in Japanese), 1973, p. 262.
9) T. Mochida & K, Ibamoto; A Study on Evaluation of the Thermal Radiation Effect —Mean Radiant Temperature Weighted with the Absorption Factor —, Memoirs of Faculty of Engineering, Hokkaido University, Japan, No. 64, 1976, pp. 1–13.
10) C. -E. A. Winslow & L. P. Herrington; Temperature and Human Life (translated into Japanese by H. Kita & N. Takemura, Ondo To Ningen — Onnetsu No Seirieiseigaku), Ningen To Gijutsusha, 1974, p. 32.
11) Committee of Human-Environment System; Human-Environment System, Part I, (Ningen-Kogakukei, Written in Japanese), Ningen To Gijutsusha, 1972, p. 178.