Expression of the radiative heat exchange for the human body and its application to modifying the original WBGT for outdoor environment

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SUMMARY

In order to calculate mean radiant temperature in an outdoor environment, we had to calculate a hypothetical sky temperature from directly measurement or an empirical formula of atmospheric radiation expressed as functions of daily mean air temperature, cloud amount, etc. The aim of this research is to propose new expression for simply calculating the radiative heat exchange in an outdoor environment. In this paper, we defined the long-wave radiation coefficient based on the ratio of atmospheric radiation to long-wave radiation from the ground to the human body and derived linearized radiative heat exchange equation in an outdoor environment to be expressed only in the ground temperature and solar radiation. We qualitatively analyzed the long-wave radiation coefficient and the radiative heat transfer coefficient. Finally, based on measured data in an outdoor environment, we proposed the empirical formulae for calculating the long-wave radiation coefficient using solar radiation or the ground temperature.

INTRODUCTION

It is necessary to represent accurately heat exchanges by long-wave and short-wave radiations between the human body and an outdoor environment in order to evaluate thermal and comfort sensations of humans in outdoor environments. The authors have already proposed a series of effective radiant temperatures as mean radiant temperature in an outdoor environment [1] [2]. One is only based on the direct radiation between the human body and the surroundings [1], and the other is based on the multiple radiations between the human body and the surroundings [2]. The effective radiant temperature based on the direct radiation requires determining a hypothetical sky temperature by use of the empirical formula of downward atmospheric radiation defined as functions of daily mean air temperature, cloud amount, etc. Therefore, the calculation of the effective radiant temperature requires not only measured data but the meteorological data. The effective radiant temperature based on the multiple radiations requires calculating incidence factor to describe the influence of multiple radiations by use of linear simultaneous equation. Consequently, it is difficult for evaluation of an outdoor environment to calculate these temperatures on-site.

In this research, to simply calculate a radiative heat exchange in an outdoor environment, we define new long-wave radiation coefficient based on the ratio of atmospheric radiation to long-wave radiation from the ground to the human body, and propose new expression of the heat exchange by radiation between the human body and an outdoor environment considering solar radiation and the ground temperature. We qualitatively analyze the long-wave radiation coefficient, and propose concrete formulae for calculating the long-wave radiation coefficient by use of measured data in an outdoor environment.
METHODS

In an outdoor environment, heat exchange by long-wave radiation occurs between humans and the ground, the sky and body surfaces such as buildings. Besides, the outdoor radiative environment contains short-wave radiation, specifically, direct solar radiation, scattered solar radiation and reflected solar radiation from the ground and buildings.

The heat exchange $R$ between humans and the environment containing short-wave and long-wave radiation is given as Equation (1). We assume the buildings' surface temperature is equal to the ground temperature and only consider reflected solar radiation from the ground.

$$\frac{R}{A_{cl}} = \varepsilon_{cl} \varepsilon_{gr} \sigma \left( (T_{cl} + 273)^4 - (T_{gr} + 273)^4 \right) \left( 1 - U_r \right) f_{ref}$$

$$+ \varepsilon_{cl} \varepsilon_{sky} \sigma \left( (T_{cl} + 273)^4 - (T_{sky} + 273)^4 \right) U_r f_{ref} - (H_d + H_s + H_r)$$

$$H_d + H_s + H_r = a \left( f_p I_{DN} + I_{SH} U_r + \rho_{gr} I_{TH} (1 - U_r) \right) f_{ref}$$

(2)

where $R$ is radiative heat exchange [W], $A_{cl}$ is surface area of clothed human [m²], $\varepsilon_{cl}$ is emissivity of clothed human body [N.D.], $\varepsilon_{gr}$ is emissivity of ground [N.D.], $\sigma$ is Stefan-Boltzmann constant ($=5.67 \times 10^{-8}$) [W/(m²K⁴)], $T_{cl}$ is mean surface temperature of clothed human [°C], $T_{gr}$ is ground temperature [°C], $U_r$ is sky view factor for the human body [N.D.], $f_{ref}$ is effective radiant area factor [N.D.], $\varepsilon_{sky}$ is emissivity of sky [N.D.], $T_{sky}$ is hypothetical sky temperature [°C], $H_d$, $H_s$, and $H_r$ are direct, scattered and reflected solar radiation absorbed into body surface [W/m²], $a$ is absorptivity of human surface [N.D.], $f_p$ is projected area factor [N.D.], $I_{DN}$ is direct solar radiation to normal plane [W/m²], $I_{SH}$ is scattered solar radiation to horizontal plane [W/m²], $\rho_{gr}$ is reflectivity of ground [N.D.], $I_{TH}$ is global solar radiation to horizontal plane [W/m²].

Figure 1 shows atmospheric radiation and the long-wave radiation from the ground in an outdoor environment. Atmospheric radiation maintains a stable condition during any season. Long-wave radiation from the ground varies with the climate condition of day. Broken line in Figure 1 demonstrates the ratio of atmospheric radiation to long-wave radiation form the ground. The ratio is distributed between 0.5 and 0.7.
We define the ratio $\Omega$ of atmospheric radiation to long-wave radiation from the ground to the human body as equation (3), and try to simplify the radiative heat exchange equation (1) between the human body and an outdoor environment by use of the ratio $\Omega$.

$$\Omega = \frac{U_r \sigma(T_{sky} + 273)^4}{(1 - U_r)\sigma(T_{gr} + 273)^4}$$  \hspace{1cm} (3)$$

where $\Omega$ is ratio of atmospheric radiation to long-wave radiation from the ground to the human body [N.D.].

$U_r$ in equation (3) denote configuration factor between the human body and the sky, and is referred to as sky view factor for the human body.

RESULTS

Substituting equation (3) into equation (1) to eliminate $T_{sky}$ yields equation (4).

$$\frac{R}{A_{cl}} = \varepsilon_{cl}\sigma[(T_{cl} + 273)^4 - (T_{gr} + 273)^4(1 - U_r) + (T_{sky} + 273)(1 - U_r)]f_{ref} - (H_d + H_s + H_r)$$

$$= \varepsilon_{cl}\sigma[(T_{cl} + 273)^4 - (1 + \Omega)(T_{gr} + 273)^4(1 - U_r)]f_{ref} - (H_d + H_s + H_r)$$

$$= \varepsilon_{cl}\sigma[(T_{cl} + 273)^2 + (1 + \Omega)(1 - U_r)^{\frac{1}{2}}(T_{gr} + 273)]$$

$$\times \left\{ (T_{cl} + 273) + (1 + \Omega){\frac{1}{2}}(1 - U_r)^{\frac{1}{2}}(T_{gr} + 273) \right\}$$

$$\times \left\{ (T_{cl} + 273) - (1 + \Omega){\frac{1}{2}}(1 - U_r)^{\frac{1}{2}}(T_{gr} + 273) \right\}f_{ref}$$

$$-(H_d + H_s + H_r)$$  \hspace{1cm} (4)$$

Defining equation (5) makes it possible to define linear radiative heat transfer coefficient $h_r$ in an outdoor environment as equation (6). $\lambda$ in equation (5) expresses the long-wave radiation properties of the human body specific to the region, date and time, and is referred to as long-wave radiation coefficient.

$$\frac{R}{A_{cl}} = h_r (T_{cl} + 273) - \lambda(T_{gr} + 273)f_{ref} - (H_d + H_s + H_r)$$  \hspace{1cm} (7)$$

Finally, convective and radiative heat exchange equation considered clothing insulation $R_{cl}$ is shown as follows:

$$\frac{C + R}{A_{sk}} = h_c (T_{sk} - T_a)F_{cl}f_{cl} + h_r (T_{sk} + 273) - \lambda(T_{gr} + 273)f_{ref}F_{cl}f_{cl} - (H_d + H_s + H_r)F_{cl}f_{cl}$$  \hspace{1cm} (8)$$

where $A_{sk}$ is skin surface area [$m^2$], $C$ is convective heat loss [$W$], $h_c$ are human’s convective heat transfer coefficient [$W/(m^2°C)$], $T_{sk}$ is mean skin temperature [$°C$], $T_a$ is air temperature [$°C$], $F_{cl}$ is thermal efficiency factor [N.D.], $f_{cl}$ is clothing area factor [N.D.].
If the long-wave radiation coefficients $\lambda$ were preliminarily calculated in each region and time, the radiative heat exchange could be calculated using solar radiation and ground temperature.

**DISCUSSION**

We qualitatively analyze $\lambda$ and $h_r$. $\lambda$ means a correction factor to calculate the heat exchange by long-wave radiation using ground temperature only. Substituting equation (3) into equation (5) gives equation (5)'.

$$
\lambda = \sqrt{1 - \left\{1 - \frac{\sigma(T_{\text{sky}} + 273)^4}{\sigma(T_{\text{gr}} + 273)^4}\right\} U_r}
$$

Because the term in brace on the right-hand side of equation (5)' is positive, the long-wave radiation coefficient $\lambda$ increases with the decrease of the sky view factor for the human body $U_r$ and is close to 1. Figure 2 shows the variation of $\lambda$ in response to the variations of $U_r$ and $\frac{\sigma(T_{\text{sky}} + 273)^4}{\sigma(T_{\text{gr}} + 273)^4}$. The long-wave radiation coefficient $\lambda$ decreases with close to an open space, which means the increase of the sky view factor for the human body $U_r$, and the decrease of $\frac{\sigma(T_{\text{sky}} + 273)^4}{\sigma(T_{\text{gr}} + 273)^4}$.

Figure 3 shows the variation of linear radiative heat transfer coefficient $h_r$ in response to that of the ground temperature $T_{\text{gr}}$ and the long-wave radiation coefficient $\lambda$. The ground temperature $T_{\text{gr}}$ in an outdoor environment ranges approximately from 0 to 50 °C and the radiative heat transfer coefficient $h_r$ varies with the variation of $\lambda$. Therefore, it is difficult to regard $h_r$ as a constant value in an outdoor environment unlike an indoor environment. The limitation of a temperature condition could regard $h_r$ as a constant value.

![Figure 2. Variations of long-wave radiation coefficient $\lambda$.](image1)

![Figure 3. Variations of radiative heat transfer coefficient $h_r$.](image2)

We determine concrete formulae for calculating the long-wave radiation coefficient $\lambda$ using the data of human experiments. Human experiments for evaluating thermal and comfort sensation in an outdoor environment were carried out from 1999 to 2004 in Sapporo and Nagoya city of Japan [3]. The experiments were conducted on the roof of a six-storied building which could be considered an open space, in a courtyard surrounded by four buildings in Sapporo city, and in a street space near a three-storied building in Nagoya city. The sky view factor for the human body $U_r$ of the open, courtyard and street space is, respectively, 0.5, 0.16 and 0.41. Experimental time was 20 or 30 min, and mean value during an experiment was used. We simultaneously measured ground temperature and solar radiation, and used for calculating the long-wave radiation coefficient $\lambda$. Atmospheric radiation was calculated from empirical formula of downward atmospheric radiation defined as functions of daily mean air temperature, cloud amount, etc.[4].
Figure 4 shows the variation of the long-wave radiation ratio $\sigma(T_{sky}+273)^4/\sigma(T_{gr}+273)^4$ in response to that of global solar radiation. Rise in the ground temperature caused by increased solar radiation decreases the long-wave radiation ratio. There is no regional difference between Sapporo and Nagoya city. However, the range of the ratio is approximately 0.1 in response to same solar radiation. Therefore, the long-wave radiation ratio $\Omega$ of atmospheric radiation to the long-wave radiation from the ground to the human body depends on the season, solar radiation and sky view factor for the human body.

Figure 5 shows the variation of the long-wave radiation ratio in response to that of the ground temperature after sunset. Because the ground surface is exchanged for only the sky after dark, there is a proportional relation between the two. There is no difference in regions or spaces which has different sky view factor for the human body. Long-wave radiation ratio ranges from 0.64 to 0.9.

The relationship between global solar radiation and long-wave radiation coefficient $\lambda$ in an open space of Sapporo city is shown in Figure 6. Increased solar radiation decreases the long-wave radiation coefficient $\lambda$, as in Figure 4. Therefore, the long-wave radiation ratio defined as a function of solar radiation or ground temperature makes it possible to calculate the long-wave radiation coefficient $\lambda$ using solar radiation, the ground temperature and sky view factor for the human body $U_r$. 

![Figure 4. Relationship between global solar radiation and long-wave radiation ratio $\sigma(T_{sky}+273)^4/\sigma(T_{gr}+273)^4$ in daytime](image)

![Figure 5. Relationship between ground temperature $T_{gr}$ and long-wave radiation ratio $\sigma(T_{sky}+273)^4/\sigma(T_{gr}+273)^4$ at night](image)

![Figure 6. Relationship between global solar radiation and long-wave radiation coefficient $\lambda$.](image)
Equation (9) shows an empirical formula of the long-wave radiation ratio based on global solar radiation derived from Figure 4. Equation (10) shows an empirical formula of the long-wave radiation ratio based on the ground temperature derived from Figure 5.

At daytime:
\[
\frac{\sigma (T_{\text{sky}} + 273)^{4}}{\sigma (T_{gr} + 273)^{4}} = 0.795 - 0.0002I_{\text{th}}
\]  

(9)

After sunset:
\[
\frac{\sigma (T_{\text{sky}} + 273)^{4}}{\sigma (T_{gr} + 273)^{4}} = 0.0035T_{gr} - 0.202
\]  

(10)

Calculating \( \lambda \) using equations (9), (10) and sky view factor for the human body \( U_r \) makes it possible to calculate the heat exchange by radiation between the human body and an outdoor environment using \( \lambda \), the ground temperature and solar radiation. However, these empirical formulae can be applied in moderate season because there are seasonal differences in Figure 4. Empirical formulae considered seasonal differences must be determined with detailed data seasonally.

CONCLUSIONS

In order to simply calculate a heat exchange by radiation between the human body and an outdoor environment, we propose a linear expression formula of radiative heat transfer based on a long-wave radiation coefficient of the human body. We qualitatively analyze the long-wave radiation coefficient and the radiative heat transfer coefficient, and derive concrete formulae for calculating the long-wave radiation coefficient from solar radiation, the ground temperature and the sky view factor for the human body using human experiments’ data in an outdoor environment.

The linear expression formula can be applied to the modification of the original WBGT for an outdoor environment [5], based on a heat balance equation between the human body and an outdoor environment [6].

REFERENCES