PREDICTIVE METHOD FOR HUMAN THERMAL COMFORT IN URBAN SPACE

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Abstract

The objective thermal environmental indicators are desired in response to trend of thermal environmental degradation in urban space. Human feeling temperature is focusing on and human thermal load was proposed as an index by authors. With using this human thermal load index, countermeasure techniques for severe thermal environment were evaluated from the perspective of human feeling. The numerical analysis was carried out for predicting human thermal load as a criterion of human thermal comfort from weather conditions. In the results, some effects on human thermal comfort were obtained.

Key words: Human thermal load, Thermal comfort, Feeling temperature

1. INTRODUCTION

Men of today are facing a variety of issues such as Global Warming and Urban Heat Island. Since more and more energy and people are concentrating in urban area, solving urban problems attracts lots of attention. Street plantings, highly reflective materials, and water retentive materials are considered to be useful for decreasing sensible heat load and creating comfortable space. As a matter of fact, the definition of 'comfortable space' is obscurity, and in this paper predictive method for human thermal comfort is judged by human feeling. Human thermal feeling is mixed senses of air temperature, humidity, radiant temperature, wind speed, metabolism, and clothing insulation. Human thermal load proposed by authors (Shimazaki, 2009) is an index which can express human thermal feeling. Therefore, some countermeasures were valued by human thermal load.

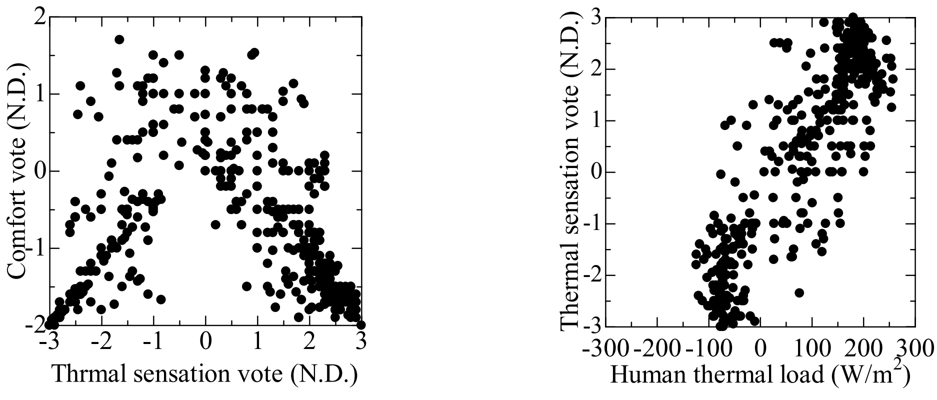
2. HUMAN THERMAL LOAD AS A COMFORT INDEX

Any heat gain or loss from thermally neutral state is considered as hot or cold sensation of discomfort. The amount of heat was focused on base on the idea, and the human thermal load was examined its effectiveness. The amount of physiology also needs to be included in the thermal comfort index which aims at application on the outdoors in the suitable form as well as the weather parameter peculiar to the outdoors, such as solar radiation and wind velocity. The human thermal load Q is calculated from **Equation 1** as a remaining amount of each energy balance items. It is objective and actually by the basis of the energy balance formula about the human body incorporating the amount of physiology.

$$Q = M - W + R_{net} - E - C \qquad (1)$$

where M is metabolism [W/m^2], W is workload [W/m^2], R_{net} is net radiation [W/m^2], E is latent heat loss [W/m^2] and C is sensible heat loss [W/m^2], respectively.

In order to grasp the effectiveness of human thermal load, the subject experiments were carried out and the physiological reaction and mental action of human body in the outdoors were observed. The surrounding weather factors and the physiological amounts of human body were measured. The horizontal solar irradiation, the reflected solar radiation from the ground, the infrared radiation from the atmosphere and ground, the air temperature, the wind velocity, the humidity and the ground temperature measured for every minute. The mental reaction was made to notify every 2 or 5 minutes as a fixed report using the consultation measure which has been



(a) Thermal sensation v.s. thermal comfort (b) Human thermal load v.s. thermal sensation
Figure 1 Relationship among human thermal load, thermal sensation, and thermal comfort

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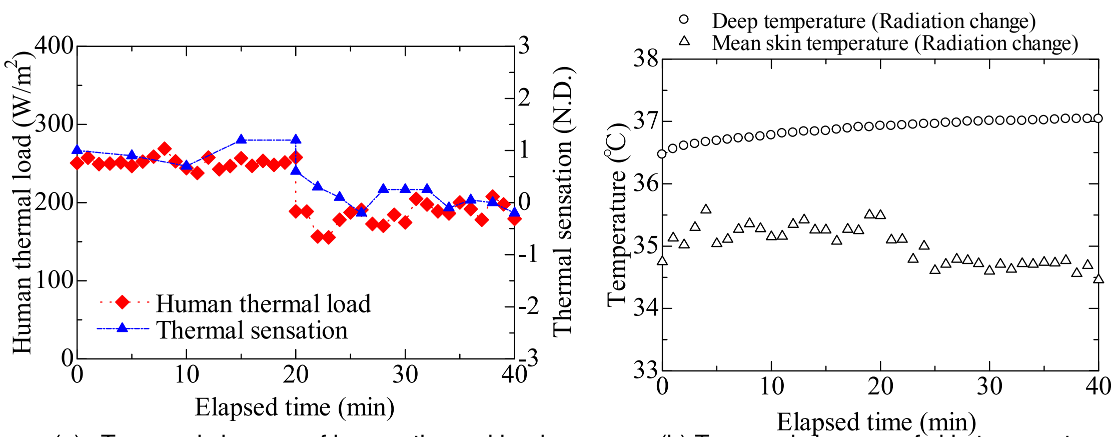
proposed from ASHRAE. Open space was selected for other experiments. Subjects were the boy students of healthy twenties and total number of subject were 46. Sensors were installed in 15 minutes before the measurement starts and subjects were accustomed to the initial state.

As shown in **Figure 1**, there is a straight line relationship between human thermal load and thermal sensation and is certain relationship between thermal sensation and thermal comfort. This means human unconsciously judge its thermal sensation on the amount of heat they receive. Human are uncomfortable with too hot or too cold, and so they feel comfort when they are on nearly neutral. As a result, a thermal sensation can be predicted by human thermal load and thermal comfort can be predicted by thermal sensation. Finally, thermal comfort can be obtained by using human thermal load. The relationship between human thermal load and thermal sensation was expressed by least mean square approximation for need of the numerical analysis below as

$$(\textit{Thermal sensation}) = 0.0146 \times (\textit{Human thermal load}) - 0.748 \qquad (2)$$

3. EFFECT OF RADIATION

Solar radiation is dominant especially in outdoor. The effect of solar radiation on human thermal comfort was examined. Some of the results are shown in **Figure 2**. Because the amount of solar radiation which human received changed, human thermal load dramatically changed after 20 minute. And the mean skin temperature decreased gradually after 20 minute when radiation change occurred, however deep temperature gradually increased through the experiment because of exposure in outdoor. In this way, radiation's strong effect on human thermal comfort was confirmed.



(a) Temporal changes of human thermal load and thermal sensation
(b) Temporal changes of skin temperature

Figure 2 Results in radiation change

4. OUTLINE OF NUMERIAL ANALYSIS

4.1. Basic conditions

This is an attempt to describe the thermal environment in urban space, and simple modeling was adopted. Some results of outdoor measurement were used as given conditions. Air temperature, surface temperature, solar radiation, infrared radiation, wind speed, and humidity were measured values at the initial. For human model, 65MN model (Tanabe, 2002) was modified for applying to outdoor and used.

The earth's surfaced heat budget was focused on, and surface temperature, air temperature, and humidity was calculated. The earth's surface heat budget is expressed as

$$C_t \frac{\partial T_{sur}}{\partial t} = R_{net} - H - lE - G \qquad (3)$$

$$R_{net} = S\downarrow - S\uparrow + L\downarrow - L\uparrow \qquad (4)$$

$$S\uparrow = (1\text{-}ref)\, S\downarrow \qquad (5)$$

$$L\uparrow = \varepsilon \sigma T_{sur}^{\;4} \qquad (6)$$

$$H = -C_P \rho C_H U \frac{\partial T}{\partial z} \qquad (7)$$

$$lE = -l\beta k \frac{\partial q}{\partial z} \qquad (8)$$

$$G = k_s \frac{\partial T_s}{\partial z}\Big|_{z=0} \qquad (9)$$

where C_t is heat capacity on surface, T_{sur} is surface temperature, t is time, R_{net} is net radiation, H is latent heat flux, lE is sensible heat flux, G is heat conduction flux into the ground, $S\downarrow$ is global solar radiation, $S\uparrow$ reflected solar radiation, $L\downarrow$ is infrared radiation from sky, $L\uparrow$ is infrared radiation from earth's surface, ref is reflectance of surface, ε is emissivity, σ is Stefan-Boltzmann's constant, C_P is specific heat, ρ is density , C_H is bulk transfer coefficient, U is wind speed, T is air temperature, z is vertical direction, l is evaporative heat, β is evaporation efficiency, k is mass transfer coefficient, q is specific humidity, k_s is heat conductivity of soil, T_s is soil temperature, respectively.

Basic equations for air is expressed as

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial z^2} \qquad (10)$$

where a is heat diffusivity.

Boundary condition is expressed as

$$\frac{\partial T}{\partial z} = 0 \quad (z = 200 \ \ \mathrm{m}) \qquad (11)$$

$S\downarrow$ and $L\downarrow$ were given by the real weather data on Jul 22nd-23rd 2008. On those days, it was very clear sky and assumed typical summer's day.

4.2. Case study

Typical improvement acts were taken up and such countermeasure techniques for severe thermal environment were evaluated from the perspective of human feeling. Since highly reflective surface material is relatively high in reflectance, the amount of heat in radiation which is absorbed on the earth's surface is small and this material can reduce environmental thermal load. Since retentive material can keep water in it and the water vaporizes slowly, temperature of the material keeps relatively low. The amount of heat storage decreases and this material contribute to thermal environment improvement. Asphalt concrete pavement is widely used and assumed as normal surface. Three cases described above were investigated. Details were shown in **Table 1**.

Table 1 Properties of materials

	ref	β
Highly reflective material	0.4	0
Retentive material	0.1	0.15
Asphalt concrete	0.1	0

5. RESULTS AND DISCUSSIONS

The results of human feeling based on human thermal load and thermal sensation at 12:00-14:00 JST on 23rd were shown in **Figure 3**. Clothing insulation was 0.68 clo and wind speed was 0.5 m/s. When retentive material is used as pavement, it may be the most comfortable space. And when highly reflective material is used, it may be most uncomfortable. These are because the amount of heat in radiation has impact on human comfort. As shown in **Figure 4**, the primary cause on human thermal load was seen on reflected solar radiation. As the reflectance becomes higher, the amount of reflected solar radiation becomes larger and human receives more heat. The difference between asphalt concrete and retentive material is small, and in the results surface modification is meaningful but not enough for improvement of thermal environment in urban space. The use of highly reflective material leads to a reduction in environmental heat load, but application for the place where there is no human activity such as roof is desired.

You may think clothing acts as cushion against solar radiation, but clothing is also not enough. For example, subject experiments with different colored clothing or naked were carried out in order to undestand the effects of clothing. The results of material color are shown in **Figure 5**. For reference, the approximate curve in steady state is drawn in **Figure 6 (a)**. The solar radiative properties were different between white and black cotton, and the values of absoptivity, transmissivity, and refrectivity were 0.22, 0.32, 0.46 for white cotton, and 0.52, 0.38, 0.10 for black cotton, respectively. However, thermal sensation does not have large difference between white clothing and black material. Naked subjects felt cooler than dressed subjects, because clothing act as cushion against not only radiation but also heat and moisture transfer from human body which is heat generator. In general, black material tends to absorb more solar energy compared with white material, and black material has higher surface temperature, but the amount of heat transferred from clothing to human skin is not so large difference among colors. That's why colors have no impact on thermal sensation. Two subjects were stood at the same time and at the same place. One of subjects was naked and another subject was dressed. The temporal changes in human thermal load are shown in **Figure 6 (b) and (c)**. There is a great deal of variation of human thermal load when the subject was naked. On the other hand, human thermal load of the dressed subject has relatively small change. The short-term temporal variation in human thermal load was caused by mainly wind. The dynamic change in human thermal load level was caused by solar radiation. If dressed, the amount of heat which human received was larger, but the range of fluctuation became narrower. The heat generated inner body was kept under clothing and kept human warm leading to discomfort, but clothing acted as cushion against outer change and kept human comfortable. It depends situation whether human feel comfort or discomfort.

All things considered, thermal comfort space can not be created by a single measure. For better thermal environment, radiation or heat flow of the whole space was required.

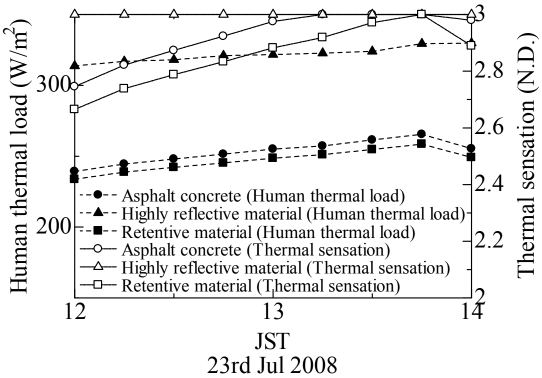


Figure 3 Human thermal load and thermal sensation

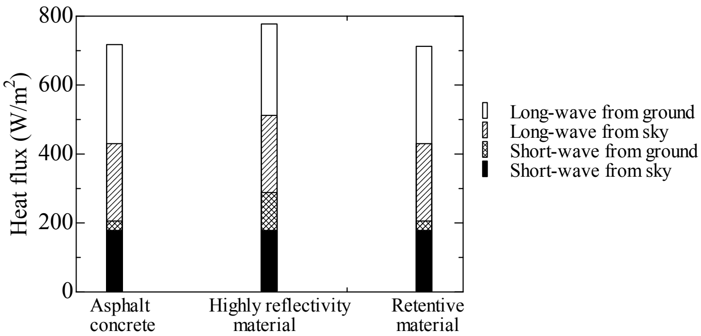
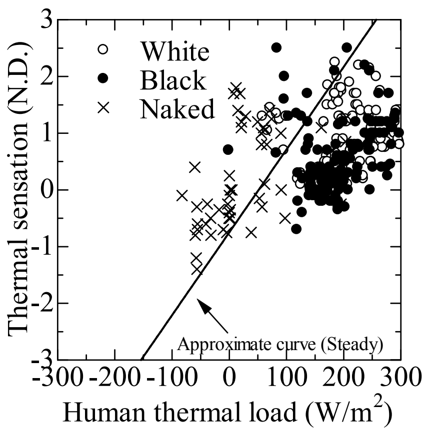
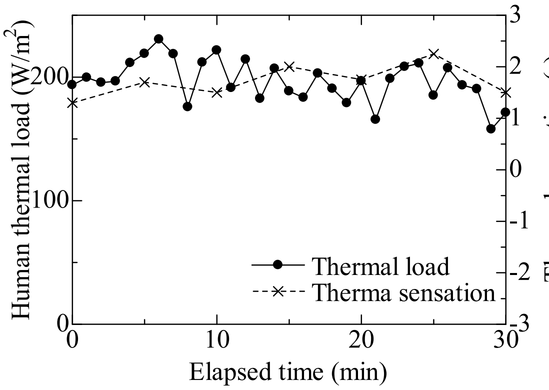


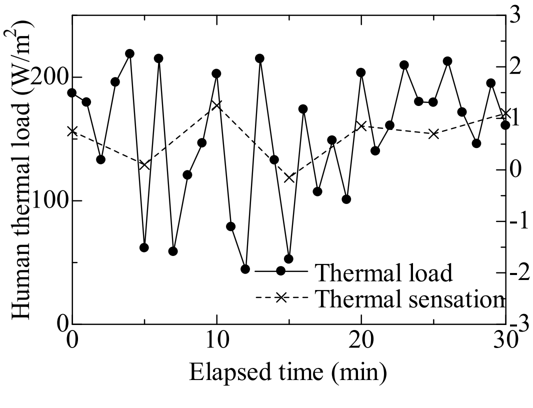
Figure 4 Amount of radiation into human body



(a) Relationship between human thermal load and thermal sensation



(b) Dressed subject



(c) Naked subject

Figure 5 Effects of clothing

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