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Prediction of outdoor human thermal states in non-uniform thermal loads

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1. Introduction

Considering the worsening situation surrounding us such as the global warming and the urban heat island phenomenon, outdoor thermal environment is a major concern to everyone. A increasing number of heat-related illnesses such as heat stroke is suspected to be due to the above mentioned high-temperature trends. Therefore, the prevention measures of severe heat exposure are necessary for outdoor planning. Thermal environmental study has a long story, and it is advisable to include as many factors as possible Previous studies found that human thermal states are recognized by multiple factors such as air temperature, humidity, radiation, wind, clothing insulation, and metabolism (Fanger 1972), and various countermeasures have been proposed and carried out for improve the environments. The present urban thermal environment, in fact, will not be fundamentally improved by these plans alone, as complex, large-scale urban planning projects are required. Generally speaking, focusing on the human thermal perception is one of key perspectives of improving outdoor thermal environment. Thus, the countermeasure of our approach regards improvement of the human experience of temperature in urban space.

Traditionally researches on thermal environment have focused on indoor situation, in fact, some indices for indoor have been widely used for biometeorological assessment in even outdoor. As the main characteristic of outdoor is mainly recognized as solar radiation and variations in time and space, existing indoor thermal environmental standards are not relevant for outdoors in this regard (Spagnolo and de Dear 2003). Thus in this study, measurements and predictions under outdoor were analyzed, namely human thermal states analysis in non-uniform thermal load was presented.

2. Method and experiment

Non-uniform outdoor thermal environment is considered in two ways; outdoor space itself and human. Radiative heat transfer has impact in outdoor, and our environment is made up of various materials such as ground surface. Therefore, properties of materials surrounding us may strongly affect our thermal condition and in outdoor. Humans occasionally experience regional thermal situations and in fact there are large differences in regional temperature and sensitivity.

2.1 Thermal environmental assessment

In order to assess the actual status of an urban thermal environment in a complex urban area, some typical situations were investigated. To develop the green-area and to use high-reflectivity ground and building cover materials were focused on in the study. The surface reflectivity is considered one of essential factors for investigating thermal formation inside urban area (Santamouris et al. 2008). Therefore, the effect of radiative properties of surfaces such as a bare soil, an asphalt road, a high-reflectance tile, a grass, and a wood was conducted (Figs. 1). The open space is assumed for these cases. The positive impacts of greening on thermal environment such as evaporative cooling, lower reflectivity and shading attract attention. In order to evaluate the effect of roadside trees on human, field measurement was conducted at Osaka Japan as shown in Figs. 2.

Meteorological measurements on a pedestrian level include global solar radiation, reflected solar radiation from the ground, infrared radiation from the atmosphere and the ground, air temperature, wind speed, humidity, and ground temperature in 1-min intervals.

(a) Bare soil *(b) Asphalt* *(c) High-reflectance* *(d) Grass* *(e) Wood*

Fig. 1 Surfaces with different radiative properties

(a) With roadside trees

(b) Without roadside trees

Fig. 2 Field measurements with/without roadside trees.

2.2 Human thermal state and perception

Human energy balance is considered to be closely associated with human thermal states. Thus, we assessed the "human thermal load," as proposed previously for outdoor environments, under all experimental conditions as an objective measurement of thermal states. Human thermal load represents the details of the effect of heat transfer near the human body and these are analyzed by divided them into measurements of metabolism, workload, latent heat, sensible heat, and net radiation (Shimazaki et al. 2011). At the same time, the study participants were asked whether they experienced any thermal sensation, and if they did, whether the experience was comfortable or if it caused discomfort; the participants recorded their answers on a fixed report in which an ASHRAE 7-point scale was used (-3: Cold ~ +3: Hot).

2.3 Regional thermal load and perception

In order to identify the effect of regional thermal load on human, the regional thermal stimulation was applied only at one regional body region under cool neutral and warm ambient temperature for 10 min. Regional thermal load was applied at seven points on the skin (forehead, upper arm, hand, pelvis, thigh, leg, and foot). The thermal stimulations were directly applied on human surface using a thermal module with PID controller for temperature. The module was secured using retainer for maintaining the same contact condition. In order to regulate each regional thermal load within a certain range, the module surface temperature was set. Temperatures on module surface, whole-body surface, and applied heat flux were measured. Whole-body thermal state, whole-body thermal sensation and regional thermal sensation were measured.

3. Results and discussion

There are so many different outdoor situations and our results are examples under some existing situations.

3.1 Thermal environment assessment

Field measurements of reflectance or albedo typically involve the use of a radiometer for measuring the incident and reflected radiant fluxes. At first, we measured reflectance of surfaces with using net radiometer. The reflectance results obtained for four different types of surfaces are shown in Table 1. With regard to surface properties, the black colored asphalt surface had the lowest reflectance, and of course high-reflectance surface had the highest reflectance.

Table 1 Reflectance of surfaces.

Surface	Solar reflectance %
Bare	22.1
Asphalt	12.3
High-reflectance	39.4
Grass	17.1
Wood	14.5

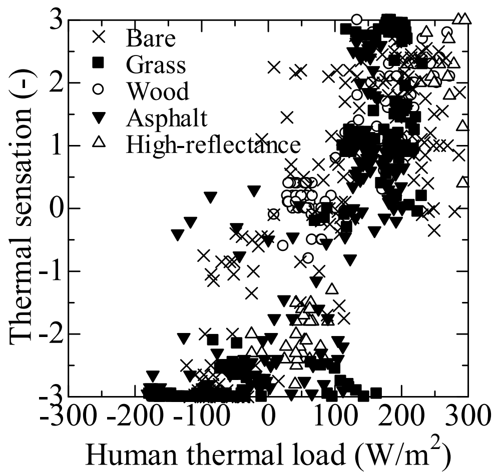


Fig. 3 Human thermal load for each experimental condition.

Human thermal states and thermal perceptions on each surface were analyzed under various weather conditions during all seasons based on human thermal load, as shown in Fig. 3. The overall human thermal load and the amount of net radiation vary according to the weather condition; however, there is a good relationship between human thermal load and thermal sensation. This means that human thermal load may be an accurate indicator of human thermal states for outdoor situations.

Next, the temporal changes of human thermal load with or without roadside trees are shown in Fig. 4. Since environmental variables changed during daytime, human thermal load varies. The amount of human thermal load with roadside trees tends to be larger in association with higher air temperatures with roadside trees. Moreover, the amount of net radiation tends to be larger. There is no hope that these low-height trees prevent solar radiation which is the main cause of human heat stress. In fact, trees have higher reflectance than asphalt concrete and asphalt mixture used on road and street, and human may receive reflected solar radiation.

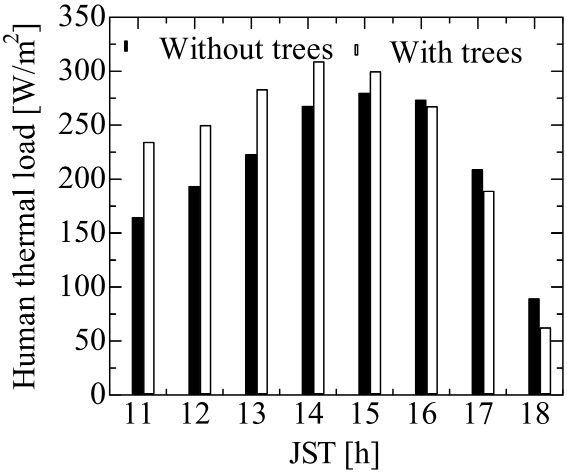
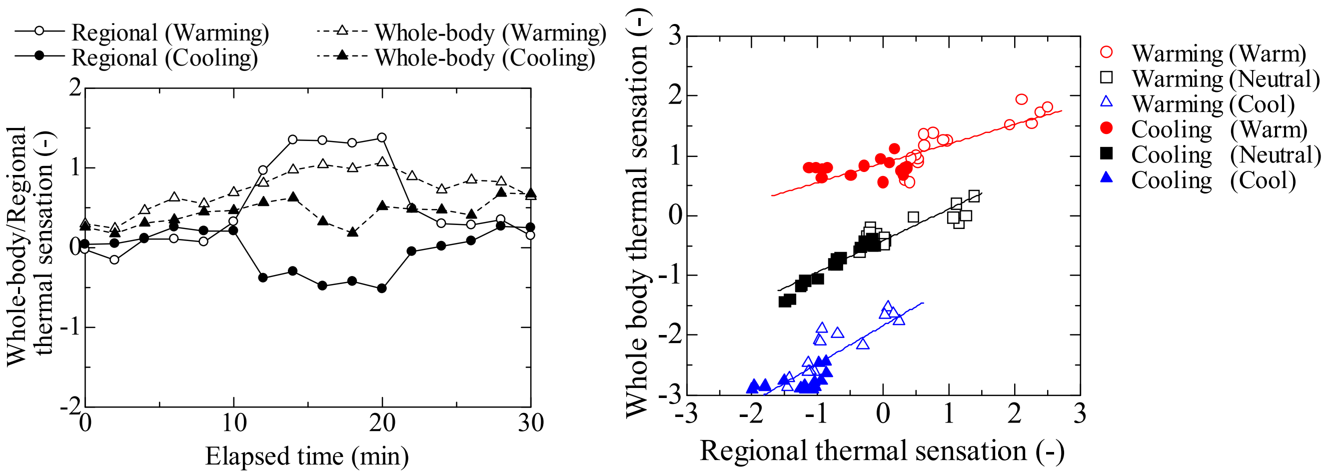


Fig. 4 Temporal changes of human thermal load with/without roadside trees.

3.2 Effects of regional thermal load

The time-dependent thermal sensation at leg obtained under each condition is shown in Fig. 5 (a). Regional and whole-body thermal sensations during application of regional thermal load rise when warming and drop when cooling. Absolute regional thermal sensation depended on the degree of absolute value of regional thermal load, consequently whole-body thermal sensation seems to correlate with regional thermal sensation as shown in Fig. 5 (b). It was found that ambient temperatures create a baseline of thermal perception. This means that even if the same amount of regional thermal load is applied, perceptions of this load might differ depending on existing thermal states.



(a) Time-dependent changes of thermal sensation *(b) Relationship between regional thermal sensation and whole-body thermal sensation*

Fig. 5 Relation among regional thermal sensation, whole-body thermal sensation, and time.

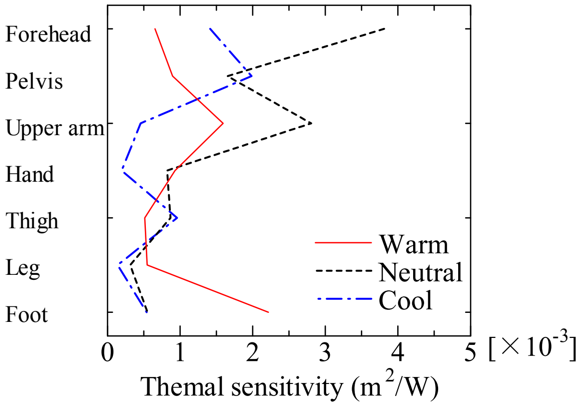


Fig. 6 Different thermal sensitivities over the body.

Thermal sensitivity could be obtained for whole-body parts, with results shown in Fig. 6. A high correlation between regional thermal load and regional thermal sensation was observed. The slope of the line represents regional thermal sensation change per unit of regional thermal load. The thermal sensitivities of parts were therefore obtained by comparing the slope of each regression line.

3.3 Summary and future works

In this paper, solar radiative properties of ground surfaces were determined for quantification of different environments. Since the human thermal condition is known to be well related to human energy balance, human thermal load can serve as an accurate indicator of human thermal states regardless of the environmental conditions. On the other hand, since regional thermal load induces regional thermal sensation, regional thermal load was correlated with regional thermal sensation. In addition, regional thermal load was correlated with whole-body thermal sensation, thus thermal sensitivity and whole-body thermal sensation was formulized by using regional thermal load.

For evaluating thermal environment, experimentation would be the best way to understand humans. In fact, the human-biometeorological assessment based on numerical analysis has been widely used, because it is easy to use. One of the most popular models would be Two-node model (Gagge et al. 1970). The main physics is focused on the thermal interaction of only two points between skin surface and core temperature. Subsequently, multi-node thermal models were introduced by extended from the two-node models. Most thermal indices were developed based on steady-state human energy-balance models, and the researchers are also attempted to extend the energy-balance model named the “human thermal load” model based on 65 Multi-Node model (Tanabe et al. 2002) to complex thermal environments. The model is counting 4 layers of tissue (core, muscle, fat and skin tissue) in 16 regional different body parts. It calculates heat transfer at each body parts, thus it have applicability to human thermal states under non-uniform environments with regional thermal load. As a future work, our new scientific knowledge of the relation between regional thermal load and thermal sensation could be combined with numerical human thermal modeling, and this enables to apply the thermal environmental assessment such as comfort, energy-saving estimation.

Acknowledgment

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