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Application of human thermal load into unsteady condition for improvement of outdoor thermal comfort

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ABSTRACT

Human thermal comfort is studied as a countermeasure to the thermal stress in outdoor urban space. Outdoors, people experience the strong impact of solar radiation in states that are unsteady and non-uniform. The feeling of comfort is a mixed sensation that can be easier to improve overall, as compared with a global large-scale effort, and can lead to improved ways of saving energy and reducing costs. Moreover, this can be directly beneficial to human experience and fulfill natural human desires. Since a thermal comfort index is a useful tool for understanding the present state and evaluating the impact of countermeasures, we examine the effects of the human thermal load, which is a thermal comfort index based on the energy balance of the human body. In a steady state, and even in an unsteady state with its variations in weather and human factors, thermal comfort values can generally be obtained by using the overall human thermal load. The reason for this is that the human thermal load takes physiological factors in account as well as weather parameters. This leads to the idea that thermal sensations follow from the human thermal load, which can then well describe a given human environment. As a result, human sensations as expressed by the human thermal load pave the way to the creation of comfortable urban spaces that require minimum expense and energy as an example of simple heat transport model focusing on urban outer structure.

1. Introduction

Challenges to environment are now a theme that is common to the entire world. The global rise in temperature is well known as 'Global Warming' and environmental measures are attracting increasing attention [1–4]. Moreover, people, products and energy are concentrated in urban areas, which causes specifically urban problems such as thermal stress, which can produce what are referred to as 'Urban Heat Islands' [5–7]. Many researches have been carried out not only for UHI but also for general urban climate. In order to mitigate the burden of the urban thermal environment, and urban heat islands as an example, a number of plans have been proposed, such as tree planting and highly reflective surface coatings, among others [8–11]. The present urban thermal environment, however, will not be fundamentally improved by these plans alone, as complex, large-scale urban planning projects are required. This is because direct improvements of air temperature, humidity, radiant temperature, or wind speed may be not possible without large-scale effort such as urban restructuring or planning, and this takes time and is costly. The countermeasure of our approach regards improvement of the human experience of temperature in urban space. In general, how one feels the temperature or experiences thermal comfort is determined by six dominant factors: air temperature, humidity, radiant temperature, wind speed, metabolism, and clothing. Since comfort is a mixed sensation, that is, humans do not feel only one isolated component, so it is difficult to establish a better thermal environment by improving just one component. The feeling temperatures that we experience, however, can be easier to improve overall, and this may lead to improved ways of saving energy and expense.

The history of thermal comfort study goes back to the concept of Effective Temperature, which was advanced by Houghten and Yaglou in 1923 [12]. This work was based on subject experiments and assumed an indoor environment in which the three factors of air temperature, relative humidity, and wind speed went into the calculations. Later, CET was proposed, which also considered

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radiation [13], and ET* was also proposed, which added the influence of metabolism and clothing [14]. SET*, which employed a two-node model, was later proposed by Gagge, and this index is now widely used as the ASHRAE standard [15]. Another well known index defined by ISO 7730 is PMV, by Fanger, which employs six factors that include both physical quantities and human quantities. PET, which was proposed by Höppe, is an index based on the energy balance of the human body [16,17]. For the past years, UTCI was developed to meet requirement for assessment in outdoor thermal environment [18]. A number of other indexes also exist. For example, the Wind Chill Index is commonly used, particularly in cold regions [19], and the Wet Bulb Globe Temperature [20] and Heat Index are used for the prevention of heat disorders. It is advisable, of course, to include as many factors as possible, particularly human elements. In this sense, a thermal index with physiological relevance has become increasingly popular [21].

In this study, desirable urban planning concepts are investigated using subject experiments based on the energy balance of the human body. Most of the existing indexes described above present some limitations in being applied to the outdoors, where the situation is so fundamentally different from an indoor environment. Solar radiation, which has the most dominant effect on the human body, is unsteady and non-uniform in the outdoors, and it also undergoes variations that can be rapid and drastic. In accordance with the aim of achieving physiological relevance, a new thermal comfort index was proposed by the authors that employs the human thermal load, and the validity of this index was confirmed in the steady state outdoors [22]. Human thermal load method is better for outdoor study, because it counts for the solar load which is a dominant factor affecting comfort in outdoor environments. Several studies indicate that the main influencing factors during summer are the mean radiant temperature [23,24]. There are many studies about human subject experiments in step-like pattern of change in condition, but none of them includes the solar radiation. The effect of radiation in outdoor thermal comfort can be considered by using RayMan model as being important [25]. In order to obtain a good estimation of human thermal comfort, unsteady responses were investigated in a way that was oriented toward human experience. What is needed is an accurate reading of the present circumstance as well as an accurate response.

The purpose of this study is to present a method for quantification and evaluation of urban thermal environment in terms of feeling temperature or subjective thermal perception through the use of a human energy balance model which is proposed by authors. Outdoor environment was assumed and the effects of transient and solar radiation were analyzed in summer season. This study shows how human experience is composed of a combination of factors. The authors not only determine the factors that constitute thermal comfort, using the human thermal load, but also present a concrete plan for how to create a better urban thermal environment focusing on urban outer structure.

2. Model of human thermal load and its validation

2.1. Human thermal load

Thermal comfort is affected by multiple factors such as radiation, heat convection, etc. Any heat gain or loss from a thermally neutral state is experienced as a hot or cold sensation of discomfort. Based on this idea, we focused on the degree of heat and examined the effect of the human thermal load. The varying degrees of physiological factors also need to be accounted for in a thermal comfort index that can be applied outdoors in a suitable manner, as well as the weather parameters peculiar to the outdoors, such as solar radiation and wind speed. The definition of human thermal load is similar to that of PET [16,17]. PET is defined as the physiological equivalent temperature at any given place. It is equivalent to the air temperature at which, in a typical indoor setting, the energy balance of the human body (work metabolism 80 W, added to basic metabolism; heat resistance of clothing, 0.9 clo) is maintained with core and skin temperatures equal to those of the conditions being assessed. The human thermal load Q is in itself the heat flux in a given condition and is calculated from Equation (1) as the remaining amount of each item of energy balance. It is an objective value that is based on an energy balance formula for the human body that incorporates varying degrees of physiological factors.

$$Q = M - W + R_{\mathrm{net}} - E - C, \tag{1}$$

where M is the metabolism [W/m^2], W is the workload [W/m^2], R_{net} is the net radiation [W/m^2], E is the latent heat loss [W/m^2] and C is the sensible heat loss [W/m^2]. Each term is described in detail below.

(a) Metabolism: Metabolism refers to the chemical reactions that occur within a living organism and that result in the production of energy. When a quiet state is maintained in a standing position, it is presupposed that the amount of energy of metabolism M is fixed at 80 [W/m^2]. During exercise, metabolism is calculated from the oxygen uptake and carbon dioxide production.
(b) Workload: Workload is defined as the amount of work with a given load over time. The amount of workload was assumed as 0 [W/m^2] in a quiet state. During exercise, workload is based on exercise on an ergometer and the body surface area. In general, the energy needed to do work is bigger than the mechanical workload alone, however, this amount of energy could be small and ignored.
(c) Net radiation: Net radiation is the difference between the incoming and outgoing radiation. The amount of net radiation R_{net} was computed for a simulated human body model in a rectangular parallelepiped (0.4 m × 0.2 m × 1.2 m). In the outdoors, the amount of net radiation is the summation of the solar radiation and long wave radiation.
(d) Latent heat loss: The heat that is consumed during the evaporation of liquid water to form a gaseous vapor is lost, and is referred to as latent heat loss. The amount of latent heat loss E from a human body was computed as the sum of perspiration evaporation heat from skin, insensible perspiration heat, and respiratory evaporation heat through breathing. Heat from the evaporation of perspiration was presumed from the threshold value in the difference between the core temperature and average skin temperature.
(e) Sensible heat loss: The energy required to raise the temperature of infiltrating or ventilating air up to the air temperature is referred to as sensible heat loss. The amount of sensible heat loss was computed as the sum of loss from the skin and from expiration.

The effects of clothing insulation are considered in terms of latent heat loss E and sensible heat loss C. For instance, the authors examined the relationship between clothing and thermal sensation by measuring various clothing thermophysical properties and doing subject experiments including unclothed body [26]. Therefore, all six dominant factors are fully considered in this index. In Equation (1), the body surface area S [m^2] for Japanese people is given as [27]

$$S = 0.00718 \times H^{0.725} \times W^{0.425} \tag{2}$$

where H is height [m] and W is weight [kg]. Since thermal sensation depends on the experience of people, and thermal sensation could be difference in various climate regions, the authors add that this research is investigated in Japan.