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Measurements and predictions of the skin temperature of human subjects on outdoor environment

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ABSTRACT

Thermal comfort in outdoor spaces is strongly associated with the quality of social life in an urban community. This study investigated dynamic outdoor thermal comfort under cold, mild, and hot climatic conditions with air temperature ranging from −0.1 to 35.0 °C. Using a total of 26 human subjects in 94 tests under these climatic conditions, this study measured outdoor thermal environmental parameters, monitored subjects' skin temperature, and recorded subjects' thermal sensation. The study found that fluctuations in wind speed and solar radiation led to changes in convective and radiative thermal loads on the human subjects. Their skin temperature and thermal sensation changed accordingly. In the cold conditions, the skin temperature of the trunk was stable at around 34 °C, while the skin temperature of the face decreased to 19 °C. This investigation developed a human heat transfer model that considers outdoor radiative heat exchange and transient heat transfer in clothing. The mean skin temperatures predicted by the model agree reasonably well with the measured data. However, the discrepancy between the predicted and measured local skin temperature under extremely cold conditions can be as large as 6 K.

1. Introduction

About 54% of the world's population lives in urban areas [1]. In cities, outdoor spaces allow citizens to exercise and socialize. A study in Japan showed that living in areas with walkable outdoor spaces increased the longevity of urban senior citizens [2]. Another study, in the Netherlands, indicated that green outdoor spaces in the living environment decreased people's feelings of aloneness [3]. In light of these physical and social benefits, it is necessary to design attractive spaces that would encourage more citizens to spend time outdoors. Among many factors that affect people's use of outdoor spaces, thermal comfort is probably the most important. A number of studies [4–8] have identified a strong correlation between outdoor thermal comfort and occupancy in outdoor spaces. For example, Lin et al. [4] demonstrated that the greatest park attendance was associated with the highest thermal comfort level.

To better understand outdoor thermal comfort, many researchers have conducted field surveys in various climate regions. For example, Nikolopoulou and Lykoudis [6] reported their findings from a large-scale study across five different European countries. The air temperature in their study ranged from 5.4 to 30.1 °C. The researchers found that 75% of the interviewees felt comfortable in outdoor spaces. Spagnolo et al. [9] investigated several open spaces in Sydney, Australia. They discovered that the outdoor neutral temperature (26.2 °C) was significantly higher than the indoor neutral temperature (24 °C). Thorsson et al. [7] studied thermal comfort in a park in an urban area in Sweden and demonstrated that psychological aspects such as expectations, experience, and perceived control influenced the subjective thermal comfort assessment. These studies have advanced our understanding of outdoor thermal comfort. Furthermore, field surveys have revealed differences in outdoor thermal comfort among various climate regions. Aljawabra and Nikolopoulou [10] conducted case studies in hot arid areas in Marrakech, Morocco, and in Phoenix, Arizona, USA. Although the climatic conditions in the two regions were similar, most subjects in Marrakech voted for "warm," while most subjects in Phoenix voted for "hot." Nikolopoulou and Lykoudis [6] found a difference of over 10 K in neutral temperature across Europe. Lai et al. [11] found that the neutral temperature range in Tianjin, China, was different from that in Europe [12] or Taiwan [13].

The discrepancies in those studies may be due to the dynamic features of outdoor thermal comfort. Since the outdoor thermal environment can change rapidly within a short period, a person's

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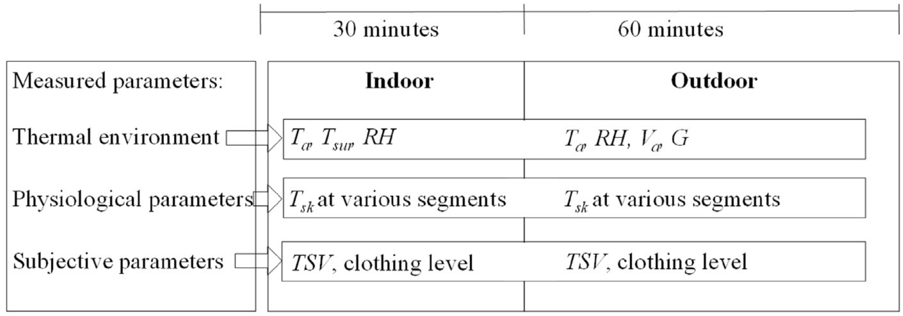

Fig. 1. Measurement procedure for the human subject tests.

skin and core temperatures will change accordingly but with a very significant decay. Hoppe [14] found that when a person walked from a neutral indoor environment to a cold outdoor environment of 0 °C, his skin and core temperature reached equilibrium after 26 h. As the skin and core temperatures of the subject decreased, his thermal sensation was likely to change. In addition, the outdoor thermal environment has large fluctuations: wind speed varies constantly, and solar radiation intensity varies with time if clouds are present. These fluctuations affect the thermal sensation of subjects. The field surveys discussed above may not have considered the thermal history of the subjects and may have recorded the thermal sensation of interviewees only at specific times. It is probable that the recorded thermal sensation had a large variation. Our literature review did not find any outdoor thermal comfort studies with a dynamic thermal history of the subjects. Therefore, it is necessary to investigate dynamic outdoor thermal comfort by considering the thermal history of subjects under a fluctuating outdoor thermal environment.

Some studies have investigated transient outdoor thermal comfort with the use of human heat transfer models. For example, Katavoutas et al. [15] employed the Institutionary Munich Energy balance Model (IMEM) to investigate the transient thermal comfort when an individual moved from an indoor to an outdoor hot environment. Their study found that skin temperature stabilized in 10 min, but core temperature continued to rise during the simulation. The modeling study has provided useful insights about changes in a person's thermal condition outdoors. The IMEM model in Katavoutas' study treated a human body as two nodes with uniform thermal-physical properties and clothing value for each node. In reality, different segments of the body have different thermal-physical properties and are insulated with different clothing levels. Furthermore, the radiative heat transfer between a human body and an outdoor environment is complicated. The sun projects short-wave radiation onto each segment at different angles, and the temperatures of the surrounding objects may not be the same. The fluctuating thermal environment continuously affects the heat transfer on a human body. Hence, it is important to develop a human heat transfer model that can account for the impact of the fluctuating outdoor thermal environment and heat transfer on different parts of the human body. This paper reports our effort and results.

2. Research method

With the use of human subjects in an actual outdoor environment, the study measured outdoor thermal environmental parameters, monitored subjects' skin temperature, and recorded their thermal sensation. At the same time, a heat transfer model was developed to predict the subjects' skin temperature. The model was validated by the experimental data.

Table 1
Numbers of subjects based on gender and age for the tests conducted in Tianjin (TJ) and West Lafayette (WL).

	Location	Male	Female	Age < 30	Age > 30	Total
Number of subjects	TJ	9	7	10	6	16
	WL	10	0	10	0	10
	Total	19	7	20	6	26

2.1. Subject tests

This investigation measured the response of human subjects to the outdoor thermal environment. Our hypothesis was that the fluctuation in the environment creates a dynamic thermal load on the human body. The changing thermal load affects the skin temperature, which determines the person's thermal sensation.

We measured thermal environmental parameters and monitored the skin temperature and thermal sensation of the subjects. To collect data from different regions, the tests were carried out in West Lafayette (WL), Indiana, USA, and Tianjin (TJ), China. The climatic conditions in the two places allow us to collect data under a wide range of thermal environments. Both cities are in "hot summer continental" climates with hot summer and cold winter. The air temperature in the summer can easily exceed 30 °C and the lowest air temperature in winter is below 0 °C. In West Lafayette, we used ten human subjects with each subject participated the tests for three to five times to yield 40 sets of data. In Tianjin 16 subjects were recruited and each of them participated the tests for three to four times, which allowed us to obtain 54 sets of data. Table 1 shows the gender and age breakdown of the subjects in Tianjin and West Lafayette. We have 19 males and 7 females participated the test. In terms of age, 20 out of the 26 subjects are younger than 30. When designing the test, we divided the tests into seven conditions and each condition covered an air temperature range of 5 K. We obtained at least 10 sets of data for each condition. The tests in West Lafayette were conducted from March 6, 2016, to September 25, 2016 and the tests in Tianjin were from May 21, 2016, to December 14, 2016. These date ranges covered cold, mild, and hot climatic conditions.

As shown in Fig. 1, the subjects first stayed in a neutral indoor chamber for 30 min to achieve a stable thermal condition; they then moved to an outdoor space and remained there for 60 min. The indoor air temperature (T_a) and relative humidity (RH) were controlled at around 24 °C and 50%, respectively. The air velocity (V_a) in the indoor chamber was kept at a minimum. The outdoor space was an open area surrounded by several low-rise buildings.

In the indoor chamber, T_a, RH, and surface temperature (T_{sur}) were measured. In the outdoor space, T_a, RH, V_a, and global solar radiation (G) were monitored continuously. In West Lafayette, the outdoor T_a, RH, direct solar radiation (G_{dir}), and diffuse solar radiation (G_{dif}) were monitored on the rooftop of one of the surrounding buildings. Global solar radiation G is the summation of G_{dir} and