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Evaluation of a multi-nodal thermal regulation model for assessment of outdoor thermal comfort: Sensitivity to wind speed and solar radiation

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ABSTRACT

People's outdoor thermal sensation varies from that indoors. The highly asymmetric solar radiation and transient wind environment are the main causes. The University of California-Berkeley developed a multi-nodal human body thermal regulation model (the UCB model) to predict human thermal sensation and comfort in asymmetric and transient indoor environments. However, few studies compared its predictions with the survey responses outdoors. In this study, subjects' thermal sensations outdoors were surveyed and compared with the UCB model predictions. Meteorological parameters were monitored using a microclimate station, and over a thousand human subjects were surveyed. Results point out that subjects were highly sensitive to the changes in wind speed, especially under low-radiation conditions. However, the UCB model failed to predict such a high sensitivity. Besides, subjects had a higher tolerance to high air temperatures in outdoor environments when the solar radiation was acceptable, but the UCB model over-predicted the TSV (thermal sensation vote) in such conditions. Both the on-site results and the predictions by UCB model showed that subjects were more sensitive to wind speed in hotter environments while they were least sensitive to solar radiation in neutral thermal conditions. This study helps to reveal the potential of a multi-nodal thermal regulation model to address the asymmetric and transient features of outdoor environments and indicates the need to further refine the model for better quantitative prediction of outdoor thermal sensations.

1. Introduction

The demand for “comfortable” living environments is always a core topic in the area of building environment [2]. Comfortable indoor environments can be created and mechanically-controlled. In contrast, it is difficult to control outdoor environments where wind speed and solar radiation change rapidly. Nevertheless, it is realized that outdoor environments have been greatly affected by the presence of building arrays. Since the 1990s, microclimates in urban areas gained notice [3]. Studies [2] have been carried out to assess factors that could affect comfort in outdoor environments. Thermal and wind effects were found to be two of the most influential factors [2]. Thermal and wind conditions can be greatly reformed by the arrangement of building clusters [4] and trees [5]. Thus, in the process of urban upgrades and city development, urban designers, architects and engineers will be continually challenged as the importance of outdoor thermal comfort is increasingly recognized. Thermal comfort is a complex concept and varies widely between objective and subjective evaluation [6]. Meteorological parameters strongly influence thermal sensation, which accounts for the objective part of thermal comfort [6]. It is widely known that six variables affect outdoor thermal sensation, including four meteorological variables (solar radiation, wind, ambient air temperature, and humidity) and two personal variables (activity level and clothing value) [3]. Many attempts to quantify the effects of these six variables in defining outdoor thermal sensation and thermal comfort has been made in recent years. For instance, Liu et al. [7] observed long-term meteorological parameters and found that air temperature was the most critical parameter in determining outdoor thermal sensation. The shading conditions were considered in the study by Johansson [8], and solar radiation was found to be a vital factor affecting PET (Physiologically Equivalent Temperature).

Thermal indices addressing these six variables have been developed to evaluate and predict thermal sensation and thermal comfort, such as PET (Physiologically Equivalent Temperature) [9], SET* (Standard

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Nomenclature

a_k	Absorption coefficients of the clothed human body in short-wave radiation; suggested value 0.7
ε_p	Emissivity of the clothed human body in long-wave radiation; suggested value 0.97
σ	Stefan-Boltzmann constant, $5.67*10^{-8}$ W/m^2K^4
$\frac{A_r}{A_D}$	Ratio of effective radiation area and Dubois surface area; the value is 0.73 for a standing person
ANOVA	An analysis of variance
CFD	Computational Fluid Dynamics
F_{i-si}	Angle factor of the room surface to the differential area
h_r	Radiative heat transfer coefficient, W/m^2K
h_c	Convective heat transfer coefficient, W/m^2K
K_i	Short-wave irradiance, W/m^2
L_i	Long-wave irradiance, W/m^2
LSD	Least significant difference
MTSV	Mean Thermal Sensation Vote
OUT-SET*	Out-Standard Effective Temperature
PET	Physiologically Equivalent Temperature
PMV	Predicted Mean Vote
TCV	Thermal Comfort Vote
TSV	Thermal Sensation Vote
RH	Relative humidity, %
T_a	Air temperature, °C
T_b	Black globe temperature, °C
T_{cl}	Measured clothing temperature, °C
T_g	Globe temperature, °C
Tmrt	Mean radiant tenperature, °C
T_{mrt-i}	Directional radiant temperature measured by the radiometer, i = 1-6
T_{si-i}	Equivalent surface temperature of the wall in the imaginary room, i = 1-6
T_o	Operative temperature, °C
$T_{skin,i}$	Local skin temperature, °C
$\frac{dT_{skin,i}}{dt}$	The derivative of local skin temperature
$\overline{T}_{skin}$	The mean skin temperature
$\frac{dT_{core}}{dt}$	The derivative of core temperature
UCB model	UC-Berkeley Thermal Comfort Model
UTCI	Universal Thermal Climate Index
v	Wind speed, m/s
SET*	Standard Effective Temperature
SPMV	Standard Predicted Mean Vote
$Sensation_{dynamic}$	Dynamic thermal sensation
$Sensation_{static}$	Static thermal sensation
W_i	Directional dependent weighting factor. With the reference shape of a standing man, 0.06 for the vertical directions and 0.22 for the lateral directions [1].

Effective Temperature) [10], SPMV (Standard Predicted Mean Vote) [10], UTCI (the Universal Thermal Climate Index) [11] and the UCB model (a multi-node human body thermal regulation model developed by the University of California-Berkeley) [12]. Several research institutes have been using these thermal comfort indices when designing and assessing urban environments. Murakami et al. [13] combined the CFD simulation results with a radiation simulation of a Tokyo city block to produce a spatial distribution map of SET* values. Middel et al. [5] increased the prediction accuracy of solar radiation spatial distribution by generating synthetic hemispherical fisheye views from Google Earth. A distribution map of PET based on the solar radiation prediction results was generated, hoping to increase the prediction accuracy of outdoor thermal comfort level [5]. Liu et al. [14] reported a simplified method combining the measured thermal parameters with the simulated wind velocity by CFD to predict pedestrian level thermal comfort around an underneath-elevated building. Wind tunnel test results were also adopted in developing a thermal comfort map based on the PET index [15]. In general, there is a strong expectation of having a tool to accurately predict spatial outdoor thermal sensation and comfort when designing a sustainable community. But how accurately the existing thermal indices can predict thermal sensation and comfort in an outdoor urban environment remains a question and further assessment is needed.

These thermal indices were mainly developed by three approaches. The most direct and simple way is to build up a correlation between thermal sensation vote and a combination of meteorological parameters (solar radiation, wind speed, air temperature, and humidity) [16]. The models developed based on this approach are called the empirical models [7]. Liu et al. [7] correlated the thermal sensation vote with four outdoor meteorological parameters: air temperature, wind speed, absolute humidity and thermal radiation, and built up empirical models for Changsha based on long-term field observation. The empirical method is the most straightforward one to determine the relationship between thermal sensation and meteorological parameters. However, it is region-specific. The correlation result can only be applied to a limited region and a group of subjects. Applying these results to model a region with a climate condition which differs from that of the experimental location should be exercised with caution [17].

The second approach is based on energy budget models, such as the PMV (Predicted Mean Vote) index [18]. The heat flux exchange between a human body and the ambient environment is the main concern of this approach. Existing thermal indices of this kind were all developed under steady thermal conditions, where subjects were assumed to reach a thermally equivalent status [18]. The thermal indices developed based on this assumption might not be suitable for the outdoors. Human bodies might be abruptly exposed to very different thermal conditions, such as simply walking from an air-conditioned indoor space (comfortably neutral condition) to an extreme outdoor environment (cold winter or hot summer). A thermally stable condition is practically impossible to be reached in this instance [18], which makes the existing thermal indices developed from energy balance models inappropriate for outdoor environments.

The third approach relates to thermo-physiological aspects [16,18] such as SET* [10], OUT-SET* [19], PET [9], the UTCI [11], and the UCB model [12]. In a nutshell, this approach involves the stimulation of the dynamic thermal regulation mechanism of a human body - the thermal receptors located in the skin and the core perceive different levels of cold and warmth, then send signals to the brain [20,21], which then initiate a sequence of physiology responses. The primitive ones were all based on the two-node model (the core node and the skin node), for instance, SET* [10,22,23], OUT-SET* [19] and PET [9]. Simply treating the human body as a two-node model often creates prediction errors when the thermal conditions are asymmetric and unstable. Xi et al. [22] discovered that the neutral SET* varied when tested near different building blocks outdoors. Huang et al. [24] found that different linear regression relations between PET and surveyed MTSV (Mean Thermal Sensation Vote) existed in different microclimates within one campus area. Human bodies are divided into more specific compartments, 12 in total and further discretized in 187 nodes, in the UTCI compared to the early-stage thermal indices. It was intended to solve the asymmetry problem by considering the heat transfer function separately for different body tissues and segments. Though this model has considered the rate of change of T_{skin} and T_{core} to cover transient conditions, its experimental validations were obtained in uniform conditions [25]. Recently, some researchers attempted to verify its application for outdoor environments: some focused on the