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Seasonal effects of urban street shading on long-term outdoor thermal comfort

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ABSTRACT

As shading, an important factor in urban environments, affects thermal environments and long-term thermal comfort, this study conducted several field experiments to analyze the outdoor thermal conditions on urban streets in central Taiwan. The RayMan model was utilized for predicting long-term thermal comfort using meteorological data for a 10-year period. Analytical results indicate that slightly shaded areas typically have highly frequent hot conditions during summer, particularly at noon. However, highly shaded locations generally have a low physiologically equivalent temperature (PET) during winter. Correlation analysis reveals that thermal comfort is best when a location is shaded during spring, summer, and autumn. During winter, low-shade conditions may contribute to the increase in solar radiation; thus, thermal comfort is improved when a location has little shade in winter. We suggest that a certain shading level is best for urban streets, and trees or shade devices should be used to improve the original thermal environment.

1. Introduction

Outdoor thermal comfort of people are affected by thermal environment, moreover, people's usage of outdoors are affected by their perception of outdoor thermal conditions[1–4]. Furthermore, outdoor thermal environments are significantly affected by the design of built environment [5–10]. Since shadings can block direct solar radiation, numerous studies examine the effects of shading on outdoor thermal environments. For instance, previous studies [11–18] quantified the height/width (H/W) ratio of urban streets to assess shading levels, whereas the sky view factor (SVF) was used in other studies as representative of shading levels [19–23].

Ali-Toudert and Mayer, who simulated microclimatic changes by applying the ENVI-met model to an urban environment in Ghardaia, Algeria [15,16], determined that the spatial distribution of physiologically equivalent temperature (PET) at the street level depended strongly on the H/W ratio of urban streets. Emmanuel et al. [13] conducted field experiments at five locations during spring in the city of Colombo, Sri Lanka. They calculated the mean radiant temperature (Tmrt) and PET using the RayMan model [24], and found that deep street canyons (i.e., highly shaded streets) improved the outdoor thermal comfort of pedestrians. Lin et al. [25] indicated that studies with few field experiments can elucidate characteristics measured (or simulated) on a particular day and likely do not represent annual thermal conditions. Therefore, they conducted several field experiments to analyze outdoor thermal conditions at a university campus in central Taiwan, and employed the RayMan model for predicting long-term thermal comfort using meteorological data for a 10-year period. The thermal comfort range of PETs of Taiwanese residents obtained in a previous study [26] was also applied as the criterion for determining whether a thermal environment is comfortable or uncomfortable.

However, some issues related to shading on urban streets need further clarification. First, previous studies have not discussed the relationship between shading and thermal comfort in different seasons. Since a thermal environment may be comfortable in summer and cold in winter under the same amount of shade, the thermal comfort of a location must be addressed in different seasons. Furthermore, thermal comfort may vary at different times of the day (e.g. hot at noon and cool in the morning); thus, one must also determine the thermal comfort distribution during a given day to elucidate the thermal conditions at different times.

Buildings on Taiwan's traditional streets are mostly residential and commercial, i.e., the first floor is rented by stores and all other floors are residential. If these buildings are not designed with an arcade on the ground floor and lack shading, people must walk beside the street while shopping, and are exposed to the outdoor climate. Thus, people may not be satisfied with their shopping experiences when they feel uncomfortable in an outdoor thermal environment, adversely affecting store revenue and reducing rental

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prices. Therefore, investigating thermal comfort on urban blocks is essential to the economy.

The aims of this study were to

- conducted field experiment in traditional urban streets in Taiwan;
- establish the prediction model for the thermal environments based on the long-term meteorological data;
- evaluate the long-term thermal comfort frequencies based on the local thermal comfort criteria;
- examine the seasonal effects of urban street shading on long-term outdoor thermal comfort.

2. Research Approach

2.1. Outdoor thermal comfort indices

Several indices that integrate thermal factors based on the energy balance of the human body, SET* [27], OUT_SET* [28] and PET [29], are employed in assessing outdoor thermal comfort. Notably, PET is defined as air temperature (Ta) at which, in a typical indoor setting (Ta = Tmrt; vapor pressure (Vp) = 12 hpa; and wind speed (v) = 0.1 m/s), the heat budget of the human body is balanced with the same core and skin temperature as those under complex outdoor conditions [30,31]. In this study, we apply PET for the main thermal comfort index for the following reasons.

The first reason is that PET have been employed in several studies of outdoor thermal comfort [32–34] and is included in guideline 3787 of the German Association of Engineers (VDI) [29]. Furthermore, the thermal comfort criteria of PET have been modified and adopted setup for different climate regions [26,35].

The second reason is that PET can be estimate by the RayMan model, has been utilized in urban built-up areas and to generate predictions of thermal comfort in outdoor environments [24,36–38]. Lin et al. [25] indicated that the PET can be easily estimated by Ta, relative humidity (RH) (or Vp), v, Tmrt, human clothing and activity in the model. If more information is offered, the Tmrt (the most important factor during hot condition when calculating PET) can be also estimated by global radiation (Gr), cloud cover (Cd), fisheye photographs, albedo, the Bowen ratio of ground surface and the Linke turbidity to include the shading effect while calculating short- and long-wave radiation fluxes. Besides PET and Tmrt, the sky view factor (SVF), i.e. the ratio of free sky spaces to the entire fisheye view at a certain location, can also be calculated using the RayMan model for subsequent analyses.

2.2. Local thermal comfort criterion for PET

Previous studies examining thermal adaptation indicated that occupant thermal sensations and preferences vary considerably due to differences in behavioral adjustment, physiological acclimatization, and psychological habituation or expectations [39], all of which may contribute to different thermal comfort ranges, i.e., the range of thermal indices at which people feel comfortable. Therefore, the thermal comfort range for a particular region may not be applicable to other regions. In this study, the thermal comfort range is acquired from a field survey of 1644 subjects in Taiwan [26]. In this survey, 26–30 °C PET was the "neutral" sensation, 18–22 °C PET was "slightly cool", 14–18 °C PET was "cool", and <14 °C PET was "cold"; additionally, 30–34 °C PET was "slightly warm", 34–38 °C PET was "warm", 38–42 °C PET was "hot", and >42 °C PET was "very hot". As these thermal comfort ranges have been applied generally in Taiwan, a hot and humid country [25], these thermal comfort ranges are applied as criteria in this study to determine whether a thermal environment is comfortable or uncomfortable for local residents.

2.3. The field experiment

This study chose streets for measurements that are almost walking spaces and with many commercial businesses (e.g.,

Fig. 1. Studied area and measurement locations in Huwei Township.