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Thermal characteristics and comfort assessment of enclosed large-span membrane stadiums

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HIGHLIGHTS

- Winter and summer experiments were done to measure temperature distribution.
- Temperature stratification, orientation and location effects are quantified.
- Inside and outside air ΔTs: 6.2 °C and 3.1 °C for summer and winter experiments.
- Winter: $-1.2 < \text{PMV} < -0.5$ and PPD > 15% with a comfortable range of 11:30–14:30.
- Summer: $2.1 < \text{PMV}$ and PPD > 99% with no comfortable range.

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ABSTRACT

Indoor thermal performance of enclosed large-span membrane stadiums is essential for evaluation of temperature characteristics and thermal comfort. The spatial- and time- dependent characteristics due to fluctuating solar irradiance suggest that theoretical analysis and numerical simulations are hard to obtain detailed and typical building performance. For this reason, field measurement is a feasible way to investigate indoor temperature characteristics and thermal comfort of enclosed large-span membrane stadiums. In this paper, a series of winter and summer experiments with respect to spatial location and time are carried out to measure temperature distribution under unconditioned empty stadium conditions, which are then utilized to assess thermal comfort with a revised PMV-PPD method.

It is found that temperature distribution inside enclosed large-span membrane stadiums depends on solar irradiance and that temperature stratification, orientation and location effects are identified and quantified. Average inside and outside air temperature differences due to enclosure capability of membrane structures are 6.2 °C and 3.1 °C for summer and winter experiments. To assess thermal comfort, a revised PMV-PPD method is employed to calculate predicted mean vote and predicted percentage of dissatisfied values. The specific values are $-1.2 < \text{aPMV} < -0.5$ and aPPD > 15%, $2.1 < \text{aPMV}$ and aPPD > 99% for winter and summer experiments. Therefore, thermal comfort of most time period requires to be improved with additional measures.

In general, this study can provide a preliminary quantitative understanding of temperature characteristics and thermal comfort for enclosed large-span membrane buildings.

1. Introduction

Indoor thermal environment of membrane buildings with thin material thickness and multi-functional utilizations is essential for evaluation of temperature characteristics and thermal comfort [1]. The complex indoor and outdoor environmental parameters are composed of solar irradiance, air velocity, relative humidity and temperature [2]. The selection and combination of typical factors for understanding indoor thermal environment need to consider specific utilizations and functions, such as small-span/large-span and semi-enclosed/enclosed.

For small-span semi-enclosed membrane buildings, Sobhi et al. performed a parametric analysis for an atrium and evaluated thermal comfort levels, finding that low thermal comfort levels were near the walls [3]. Kim et al. carried out field experiments for three refurnished arcades and concluded that indoor environment was greatly affected by size, roof material and ventilation opening [4]. He et al. revealed that

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solar irradiance through membrane roofs had a greatest impact on thermal environment during the daytime and that mean radiant temperature at the central part went higher than air temperature since radiation cooling of ground and walls was obstructed [5]. In general, thermal performance of these membrane buildings needs to be improved to meet satisfactory thermal demands while maintaining basic requirements, such as high light transmittance and suitable utilization space. For large-span semi-enclosed membrane buildings, Lestinen et al. estimated thermal performance of a multipurpose arena during ice hockey and concert activities, and showed that the difference between numerical and experimental results was due to accuracy of boundary conditions and uncertainty of concert equipment loads [6]. Sofotasiou et al. concluded that thermal comfort of spectators and players in a semi-enclosed stadium could be achieved with the consideration of high-performance materials, design configuration and solar energy utilization during the conceptual design phase [7]. Elnokaly et al. pointed out that techniques used for evaluating thermal behavior of conventional buildings are not adequate for tensile fabric membranes, suggesting that it is necessary to form basic guidelines to inform outline design stage and predictive tools for detailed design [8]. For these reasons, analyzing thermal performance of membrane buildings needs to consider many factors to achieve reasonable thermal comfort.

For enclosed membrane buildings, the fluid characteristics become complex due to enclosed space and high sunlight transmittance. In this case, fabric buildings and ETFE cushions are two typical small-span enclosed membrane buildings. Zaki et al. focused on laminar free convection in an enclosed fabric building and concluded that heat transfer coefficient was two to three times higher than that of a similar smooth surface [9]. Kim et al. investigated thermal performance of enclosed arcades with wind tunnels and computational fluid dynamics (CFD) simulations, showing that these membrane structures required additional air-conditioning equipment [10]. Elnokaly et al. investigated the effects of forms and orientations on comfort level within membrane enclosures. It is obtained that CFD results were similar to data obtained from wind tunnel tests [11]. Tsujihara et al. evaluated thermal environment inside an enclosed arcade located in the area with mild and sunny climate, and revealed that three fourth of radiant equivalent temperature was caused directly and indirectly by solar radiation [12]. Antretter et al. utilized a CFD model to estimate temperature and velocity fields in terms of temperature difference of ETFE cushions [13]. Hu et al. assessed thermal performance of ETFE cushions integrated photovoltaics and demonstrated that temperature field was strongly dependent on PV locations [14,15]. In general, thermal performance of these small-span enclosed membrane buildings can be used as the basis for understanding enclosed large-span membrane structures but need to consider energy generation, transfer and consumption [16].

The enclosed large-span membrane buildings can reach large span, ensure natural light level and save energy under specific conditions, compared with traditional buildings. The special shapes and functions of membrane structures (large volume and building aesthetics) can be used as stadiums and swimming pools [17]. The corresponding thermal comfort is more critical than semi-open buildings considering air quality and thermal comfort [18]. Although enclosed large-span membrane buildings have been utilized for several decades, detailed thermal performance is still not well-understood as heat capacity of membrane materials is lower than those of concrete and steel, and the effects of outdoor environmental factors are more crucial than those of steel and concrete structures. Moreover, the complex influencing factors are dependent on time and spatial location, suggesting that theoretical analysis with simplifications and numerical simulations without suitable validations are hard to obtain typical characteristics and quantify building thermal performance [19]. Therefore, using experiments to investigate building performance of membrane stadiums can address thermal characteristics and thermal comfort with typical data, i.e., two extreme conditions (summer and winter). Furthermore, as multifunctional public places for holding ceremony events and sports activity, the evaluation of thermal comfort is indispensable for enclosed large-span membrane stadium. However, after a careful survey of the literature, it appears that this topic has not been well-addressed in response to location, time and weather. This paper thus focuses on indoor thermal environment of an enclosed large-span membrane stadium under unconditioned empty conditions and investigates corresponding thermal comfort with a revised method.

The composition of this paper is organized as follows. Field experiments with experimental conditions and specific considerations are presented in Section 2. Temperature analysis and comparisons in terms of orientation, location and time are analyzed in Section 3. Moreover, indoor thermal comfort is assessed and quantified with a revised PMV-PPD method. Finally, basic observations and useful values are summarized in the Conclusions.

2. Methodology

2.1. Site descriptions

The enclosed large-span membrane building is located in southwest area of Shanghai (31° north latitude and 121° east longitude). Shanghai, a coastal city with the sea level of 2 m, is within a humid subtropical climate from the perspective of the world [20]. The average yearly temperature and humidity fluctuate within a temperature range of 4.8–28.6 °C and humidity range of 71%–79%. The varying environmental conditions result in extreme high temperature in July and humidity cold in December. The high temperature caused by heat island effects [21] can result in 42 °C and low temperature in combination of high humidity can result in uncomfortable feeling.

A bird's eye view and indoor picture of the enclosed membrane stadium are shown in Fig. 1. Considering the multifunctional utilizations, the north area is used for parking while other surrounding area is

Fig. 1. Bird's eye view and indoor pictures of the enclosed large-span membrane building.