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Two-layer ETFE cushions integrated flexible photovoltaics: Prototype development and thermal performance assessment

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ABSTRACT

ETFE (ethylene tetrafluoroethylene) cushion integrated flexible photovoltaics (PV) is an extension of building integrated photovoltaics into membrane structures, which could be near zero-energy, sustainable and environmental-friendly buildings. This paper focused on a two-layer ETFE cushion integrated flexible photovoltaics with experimental study and theoretical analysis. Field experiments on a prototype were carried out to investigate temperature distribution and characteristics. It is found that temperature distribution was the result of solar irradiance, incident angle and surface curvature of ETFE cushion and that solar irradiance had an essential effect on temperature distribution. The theoretical thermal model was developed based on energy balance equation and the corresponding differential equation was solved by the Runge-Kutta method. Maximum temperature difference of 3.3 K between experimental and numerical results demonstrated that this thermal model could predict PV temperature appropriately. Furthermore, a modified equation to determine heat transfer coefficients was proposed and average heat transfer coefficients of PV and ETFE foil were 4.89 W/(m^2 K) and 4.39 W/(m^2 K). In general, this study could provide basic values and observations for investigating thermal performance of ETFE cushion integrated flexible photovoltaics.

1. Introduction

Accurate temperature distribution and appropriate temperature characteristics are indispensable for investigating thermal performance [1], comfort index [2] and energy consumption of buildings [3]. Temperature distribution is complex as it depends on many influencing factors, such as weather conditions (solar irradiance, wind velocity and directions) [4], building materials and structure types [5]. This temperature complexity indicates that theoretical analysis ignoring partial factors to facilitate derivation and calculation cannot acquire all typical temperature characteristics [6]. Moreover, theoretical results need to be validated with field data under similar weather and building conditions. These considerations are also appropriate for numerical simulations which require original experimental data as initial or boundary conditions. Therefore, a suitable way to obtain appropriate temperature distribution is field experiment. It can provide necessary data to validate theoretical and numerical results as well as modify the software that developed for evaluation of building thermal performance.

Generally, two-dimensional temperature distribution and thermal performance of various conventional buildings could be measured with non-destructive and non-invasive infrared thermography method [7,8]. In this case, Avdelidis et al. presented temperature distribution of historic structures and found that thermography could be considered as a valuable appraisal tool for preservation and protection of cultural heritage [9]. Clark et al. focused on application of infrared thermography to concrete bridges and concluded that infrared thermography could identify known areas of delamination in concrete bridge structures [10]. Lehmann et al. estimated surface temperature distribution of a concrete building under a multitude of climatic parameters such as air and sky temperature, wind, solar irradiation, thermal transmittance and emissivity [11]. Nardi et al. evaluated U-value with thermography for a residential building and compared experimental results with available results [12]. They recognized that

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this method was acceptable under night conditions and discrepancies were related to solar irradiance. These acceptable temperature conclusions of conventional buildings suggested that this method could be valuable for building integrated photovoltaics (BIPV) as temperature gradient of BIPV applications was obvious caused by PV photothermal effects. For this topic, Bazilian et al. proposed preliminary results and observations of a building integrated photovoltaics [13]. Athienitis et al. estimated temperature gradients inside concrete walls integrated photovoltaics and revealed that infrared thermography method can identify typical characteristics [14]. Carmeliet et al. concluded that highly non-uniform surface temperature distribution over the PV modules integrated into buildings was related to interacting of natural convection, forced convection and complex three-dimensional flows patterns [15,16]. These satisfactory results of common buildings and BIPV applications revealed that infrared thermography was reasonable for new building types and its BIPV applications, such as ETFE (ethylene tetrafluoroethylene) cushion roof.

ETFE cushion structure with capability of lightweight, high-transmittance and self-clean is one of the most important branches of membrane structures. ETFE cushion structure is generally used for stadiums and airport terminals where architectural aesthetics, thermal physics and structural behavior are indispensable [17]. It has some essential characteristics in terms of building materials and structure types. In detail, high light transmittance of ETFE foil and air impermeability of ETFE cushion could lead to high temperature inside the cushion roof and standard prefabricated modular ETFE cushion could meet demands of complex spatial structures [18]. In fact, these characteristics are consistent with excellent performance of flexible PV under high temperature [19], resulting in membrane structures integrated photovoltaics [20,21]. Therefore, ETFE cushion structures integrated PV with less energy demand due to photovoltaic and photothermal effects could be near zero-energy, sustainable and environment-friendly buildings [22,23]. In general, temperature characteristics of ETFE cushion roof could be a preliminary study for ETFE cushion facades since influencing factors for facades are complex, especially relative angle between building orientation and sunlight angle. Therefore, understanding temperature characteristics of ETFE cushion roof integrated photovoltaics is meaningful and useful. The corresponding conclusions and summaries can facilitate future research on temperature distribution of this building and its integration. Unlike complex construction of three-layer ETFE cushion roof with PV integrated on its middle layer and high maintenance cost during its lifetime [24], two-layer ETFE cushion with PV integrated on external surface of top layer is effective to build. Acceptable conversion of solar energy and low maintenance cost could be achieved with reduction of high PV temperature on structural ETFE foils due to air movement [25], resulting in better structural performance. As temperature distribution of building integrated photovoltaic depends on specific integrations and detailed temperature distribution of two-layer ETFE cushion integrated PV is not available, this paper investigated temperature distribution of a typical two-layer ETFE cushion integrated PV under actual environmental weather conditions.

Infrared thermography widely used to obtain temperature distribution is not commonly used for long-span membrane structures. However, temperature distribution of ETFE cushion roof can be investigated with infrared thermography considering the following reasons. ETFE cushion roof is made of standard prefabricated modular ETFE cushion with typical dimensions ranging from 1 to 4 meters. This configuration means that temperature distribution could be investigated with one typical modular ETFE cushion. Moreover, mechanical properties of ETFE foils decreased dramatically with temperature increase [26,27], especially for ETFE cushion roof integrated photovoltaics. Temperatures obtained from preliminary experimental study fluctuated dramatically with environmental conditions (i.e., solar irradiance and ambient temperature) [25,28]. Therefore, utilizing infrared thermography to estimate temperature distribution of a typical modular ETFE cushion integrated photovoltaics is essential to obtain overall temperature distribution and to determine heat transfer coefficients of buildings. This is the main standpoint of this study since temperature characteristics of two-layer ETFE cushion roofs integrated photovoltaics are not available after a careful survey of the literature.

In the present study, an experimental prototype composed of a two-layer ETFE cushion and flexible PV was developed and a series of field experiments under summer sunny condition were carried out. A theoretical thermal model for flexible photovoltaics was proposed according to energy balance equation and solved by the Runge-Kutta method. Furthermore, a modified equation to determine heat transfer coefficients of PV and ETFE foil was presented. Finally, typical observations and useful values on thermal performance were summarized in the Conclusions.

2. Experiments

2.1. Experimental prototype

As mentioned in the introduction, experimental prototype is composed of two-layer ETFE cushion roof and flexible PV. As ETFE cushion structure is relatively new compared with concrete structures [29] and characteristics of flexible PV are different from those of silicon PV [30], some basic principles of ETFE cushion and flexible PV are meaningful for understanding this new BIPV application.

For ETFE cushion structure, it is suitable for stadiums and airport terminals with the capacity to meet the demands of thermal insulation and light level. Generally, common ETFE cushion types are roofs and facades, such as the National Aquatics Center for the 2008 Olympic Games. Flexible ETFE cushion shape is a result of dynamic inner pressure, varying loads and inevitable leakage. Therefore, the amorphous silicon photovoltaic panel is a suitable choice for dynamic flexible ETFE cushion roof to utilize solar energy. For flexible PV, it is made of transparent contact-layer, blue cell, green cell, red cell, reflecting metal-layer and flexible substrate [31]. This configuration could result in high efficiency due to light spectrum splitting capacity and flexible substrate allows it to be integrated on curved surface compared to Si PV [32]. These PV characteristics correspond well with demands of ETFE cushion roof. This is the fundamental point of ETFE cushion roof integrated flexible PV.

The experimental prototype, shown in Fig. 1, is a typical element with accessary components, such as steel structure, aluminum frame and ethylene-propylene-diene monomer (EPDM) robber strap. Thickness of the ETFE foil was 250 μm and design parameters for ETFE cushion were pressure of 300 Pa and pre-stress of 1 MPa. The steel structure supported a two-layer ETFE cushion with dimensions of 2900mm $\times$ 1900 mm $\times$ 450 mm in length, width and height, respectively. Two PVs with dimensions of 1410 mm $\times$ 394 mm were symmetrically installed with ETFE bags to avoid destructive actions on top external surface of the two-layer ETFE cushion roof. At one corner of the bottom layer, a pressure sensor with maximum error of 5 Pa was equipped to detect air pressure inside ETFE cushion during tests and was connected to a programmable logic controller (PLC), which could control a blower and valves to inflate or deflate ETFE cushion roof.

2.2. Measurement setup

As stated previously, infrared thermography converting infrared irradiation into a color visual image is employed to investigate temperature distribution [33]. A brief review on working principles