Numerical Analysis of Photothermal-structural-fluid Properties of PV-ETFE Cushion roof using Multiphysics Models

Yue Yin, Wujun Chen*, Jianhui Hu

*Space Structure Research Center, Department of Civil Engineering, Shanghai Jiao Tong University
Room A302, Ruth Mulan Chu Chao Building, 800 Dongchuan Road, Shanghai, China
E-mail: cwj@sjtu.edu.cn

Space Structure Research Center, Department of Civil Engineering, Shanghai Jiao Tong University

Abstract

In latest decades, ETFE (Ethylene-tetrafluoroethylene) membrane structure has been widely used in large-span buildings in virtue of their attractive advantages such as light weight, impact resistance, high light-transmittance, stable chemical property and decent self-cleaning property. PV (Photovoltaics) can invert solar energy into electricity based on photoelectric effect, owning fantastic attributes of good flexibility and high temperature adaptability. The conception of PV-ETFE cushion roof is proposed to realize the combination between transparent ETFE cushion and flexible solar cell, making it possible to gather both photoelectricity and solar irrational heat simultaneously which can be used for building to reduce extra energy consumption. However, high temperature brought by solar irradiation can affect mechanical behaviors of ETFE materials and PV's converting efficiency due to their remarkable thermal sensitivity. Hence, it is necessary to conduct research on comprehensive properties of the roof in order to find a feasible way to collect the heat energy and guarantee the structural health of ETFE cushion. But it is unrealistic to perform experiments to measure photothermal-structural-fluid parameters of PV-ETFE cushion except its surficial and internal temperature at several points, because of limitation of measuring approaches, and the roof system's complex long-term, time-varying and dynamic features under multiple physical fields. From this perspective, a reasonable numerical analysis is needed to help investigate comprehensive performance of this kind of energy-saving roof system.

Numerical simulation was conducted in COMSOL Multiphysics software based on the on-site test of a three-layer PV-ETFE cushion roof in summer. Heat transfer module, solid mechanics module, membrane module, and fluid flow module were all taken in into consideration in the multi-physics model to reflect the real condition. There were three multi-physics interfaces coupled in this analytic model, including thermal expansion, no-isothermal flow and temperature coupling. A solar radiation model was induced to describe the heat transfer process from environment to the PV-ETFE cushion. In order to calculate structural response to internal pressure of the cushion, elastic constitutive model was applied to reflect mechanical behaviors of ETFE foils. Besides, elastic modulus of ETFE foils was set to vary with temperatures to show the thermal sensitivity of these materials when calculating thermal stress. Simplified as natural convection, internal air flows were characterized by k-ε turbulent flow model. Furthermore, it is worthwhile mentioning that time-dependent solver with time range from 9:00 to 17:00 is applied in this study to reflect coupling behavior variation during one daytime.

Analytical results of temperature variation on the cushion surface were compared with the on-site test to verify reliability of this multi-physics model. Numerical simulation reveals how temperature distributed and how air inside the cushion flowed as external environment changed. In addition, stress and displacement of the ETFE cushion, two critical indexes to determine whether ETFE foils failed, were obtained under both pressure and temperature loads. To sum up, results and conclusions from this study can help optimize the structural design of PV-ETFE cushion system and finding effective method to collect and reserve heat energy in the roof.