Solar Energy 162 (2018) 289–299

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

On-site measured performance of a mechanically ventilated double ETFE cushion structure in an aquatics center

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ARTICLE INFO

Keywords:
ETFE cushion
Mechanically ventilated cavity
Solar radiation
Indoor thermal environment

ABSTRACT

An ethylene tetrafluoroethylene (ETFE) cushion structure is an attractive approach as the building façade for aesthetic and sustainability reasons. This paper focuses on the operating performance of mechanically ventilated double ETFE cushion structure and indoor thermal environment in the National Aquatics Center of China, the largest building in the world utilizing the ETFE cushion structure as its building façade. Without mechanical ventilation in the cavity, the cavity air temperature reaches as high as 46–57 °C with a solar irradiance ranging 300–800 W/m^2. It results in a sensible load of 78–238 W/m^2 in the large space of the aquatics center without shading devices. Air temperature in the cavity could be decreased by 7.3–10.5 °C by virtue of a mechanical ventilation with an air flow rate of 830,000 m^3/h. A total heat quantity ranging 2300–5800 kW is evacuated in the cavity with a heat exhaust efficiency ranging from 9.62 to 26.98. The inner surface temperature of the building envelope is significantly decreased with the help of mechanically ventilated cavity integrated with shading devices. It contributes to a lower black globe temperature in the occupied zone and a lower indoor heat gain through longwave radiation and air convection. Furthermore, preliminary test results of natural ventilation in the double ETFE cushion structure reveal its feasibility and potential for energy conservation.

1. Introduction

There is an architectural trend towards greater building transparency, strengthening the interaction between outdoor and internal spaces. A wish to provide environmentally sensitive and aesthetically pleasing buildings has increased the use of glass in buildings as atria and skylights. However, there are many circumstances where glass is not a viable option because of the building geometry. Hence, a membrane structure which is commonly built with new materials such as ethylene tetrafluoroethylene (ETFE) (Saarinen et al., 2006; Hu et al., 2014), is applied as an alternative to glass via the flexibility of ETFE membrane for curvature of the building façade. The shape of ETFE structure is formed as the cushion with two or more ETFE layers welded at the perimeter and inflated by overpressure (Galliot and Luchsinger, 2011; LeCuyer, 2008). The light-transmittance of the ETFE is over 90% which is higher than that of ordinary 6-mm single glazing. Besides, ETFE is 100% recyclable and requires minimal energy for production and installation (Robinson-Gayle et al., 2001). Nowadays the ETFE cushion structure gains architects' favor. The main reasons include its attractive aesthetic value, transparency properties and the fact that it allows a large amount of daylight to enter the building without glare. Numerous large-scale public buildings, such as stadiums and railway stations, are constructed with ETFE cushions as the roofs or building envelopes (Robinson-Gayle et al., 2001). The representative architectures, for instance, are the Allianz Arena in Germany as a soccer stadium (2006), the National Aquatics Center in China as an Olympic facility (2008) and the Anaheim Regional Transportation Intermodal Center in USA (2014) (LeCuyer, 2008).

With transparent or translucent ETFE membranes, the indoor environment is characterized by high-intensity solar radiation and at the risk of overheating on warm sunny days in summer. Maintaining thermal comfort of the occupied zone and reducing energy consumption for cooling are crucial tasks of the air-conditioning systems in these buildings. Currently, double skin facades (DSF) are used to better the thermal energy performance of building facades with high glazing fractions (Balocco and Colombari, 2006; Gavan et al., 2010; Pomponi et al., 2016). DSF is the building envelope formed by two layers (internal layer and external layer), separated by a ventilated air cavity in order to evacuate the solar radiation absorbed by the facades (Quesada et al., 2012). Compared with a single skin façade building, the DSF building achieves a reduction in cooling load while improving the thermal comfort in temperate or tropical climate (Faggembauu et al.,

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https://doi.org/10.1016/j.solener.2018.01.042
Received 8 December 2016; Received in revised form 13 January 2018; Accepted 15 January 2018

Nomenclature

c_p	specific heat capacity of the air (kJ/(kg K))
g	gravitational acceleration (N/kg)
P_{ex}	energy power of the exhaust fans (kW)
p	thermal pressure (Pa)
Q_{ex}	heat discharge capacity of mechanical ventilation (kW)
t_{ex}	temperature of the exhaust air (°C)
t_o	outdoor air temperature (°C)
T_{cav}	air temperature in the cavity near the roof (°C)
$T_{ceiling}$	inner surface temperature of the ceiling (°C)
T_{in}	air temperature in the occupied zone (°C)
$\dot{V}$	air flow rate of the mechanical ventilation (m^3/s)
ρ_o	outdoor air density (kg/m^3)
ρ_a	density of air in the cavity (kg/m^3)
η_{ex}	heat exhaust efficiency of mechanical ventilation (dimensionless)

2003; Pomponi et al., 2016; Zhou and Chen, 2010). Contrast to the conventional DSF on an individual window element basis, a multi-storey DSF has the cavity extended over the entire building (Ghaffarianhoseini et al., 2016). The multi-storey DSF presents a greater temperature gradient along the cavity due to its height. Consequently the pronounced stack effect accentuates the exit of the captured warm air from the top of the cavity, resulting in a lower temperature inside the cavity and a lower heat gain inside the room (Mingotti et al., 2011; Joe et al., 2014). A double ETFE cushion structure integrated with a mechanically ventilated cavity is employed in the National Aquatics Center for Beijing Olympic Games, motivated by the desire to combine the transparent ETFE membrane façade of modern buildings with energy efficiency and inspired by the thermal performance of DSFs. This is also the subject of the current paper.

Performance of the DSF is identified as influenced by the following factors: the depth and height of the cavity, the shading device within the cavity and the solar irradiance (Barbosa and Ip, 2014; Haase et al., 2009). The narrower cavities present a sharper temperature gradient and a stronger natural ventilation which leads to a more effective extraction of the warmer air through the cavity. While a higher air temperature in the cavity results in a higher heat transfer towards the internal space. Thus, the cavity depth should make a balance between air extraction and heat transmission to the internal room (Radhi et al., 2013). The cavity depth could vary from 15.4 cm to 120 cm (Kim et al., 2011; Mingotti et al., 2011; Pasquay, 2004). Height difference between the inlet and outlet openings of the cavity also plays a crucial role in the magnitude of the thermal buoyancy in DSFs. The cavity height is usually less than 20 m (Anđelković et al., 2015; Joe et al., 2013) in current multi-storey DSF buildings. Additionally, studies on the effect of solar radiation to the cavity indicate that the cavity air temperature of DSF exceeds the surrounding air temperature by around 20 °C in sunny days when there are no shading devices (Chan et al., 2009; Gratia and De Herde, 2007). However, the width and the height of the ventilated cavity in the double ETFE cushion structure of the National Aquatics Center are 3.5 m and 33 m respectively, obviously beyond previous studies. Load characteristics and thermal performance with different solar irradiance and shading devices of the DSF in such scale needs to be investigated. Various models have been built for the prediction and analysis of DSF performance, including analytical and lumped models (Park et al., 2004), non-dimensional analysis (Balocco and Colombari, 2006), network models (Tanimoto and Kimura, 1997), zonal models (Jiru and Haghighat, 2008), airflow network models coupled with energy simulation (Mateus et al., 2014) and Computational Fluid Dynamics (CFD) simulation for ventilated facades (Safer et al., 2005; Xue and Li, 2015). However, there are still limited buildings which actually use DSFs. Furthermore, there is less information on the actual operational behavior and operating performances of DSFs or double ETFE cushion structure.

The National Aquatics Center of China is the largest building in the world utilizing an ETFE cushion structure as its building façade. This paper concentrates on the operating performance of the mechanically ventilated cavity in the aquatics center under various outdoor solar irradiances in summer. Comparative experiments are performed to quantitatively analyze the impact of mechanical ventilation and shading devices in the cavity on indoor thermal environment and heat gain of the adjacent air-conditioned zones. The test results provide guidance for future applications with respect to both design and operation.

2. Description of the building and the double ETFE cushion structure

The National Aquatics Center with iridescent bubble wrapped rectangular box shaped structure is one of the best venues of the 2008 Beijing Olympics. The aquatics center (Fig. 1) is located in Beijing, China, covering a square with a length of 177 m. The aquatics center covers an area of 31,329 m^2. Its total building area is 87,283 m^2 with two floors underground and four floors above the ground with a height of 33 m. The aquatics center has undertaken plenty of international and domestic competition events after the Olympics, offering the venue as a resident performing arts theater, holding large-scaled painting and calligraphy exhibitions and offering open visit to public. By the end of 2015, the aquatics center has received 17.7 million tourists and severed as a swimming fitness provider for 820,000 people.

2.1. Mechanically ventilated double ETFE cushion structure

The most notable innovation of the aquatics center is its building façade. All the external facade is covered by double translucent pillowed ETFE membranes. The interior is awash with light akin to sunlight glowing through rice paper during the day, while at night the building glows vibrantly. A large air cavity with sparse steel bracing

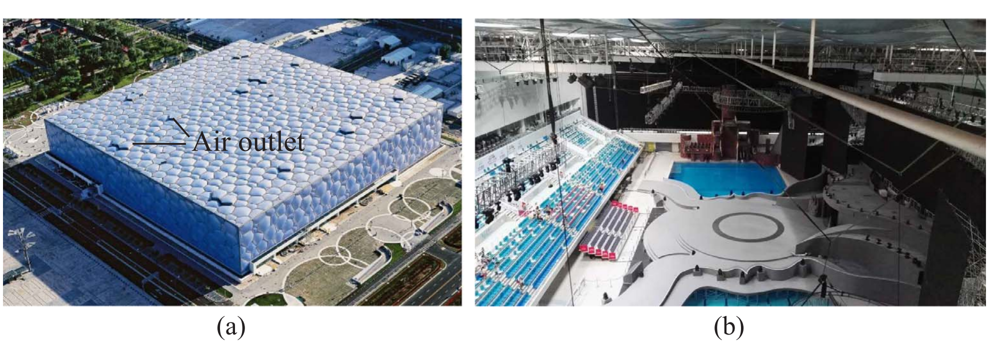

Fig. 1. Aquatic center: (a) Building façade from an aerial photo; and (b) interior view of competition venue.