Energy and Buildings 159 (2018) 558–571

Contents lists available at ScienceDirect

Energy and Buildings

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

Experimental study of a local ventilation strategy to protect semi-exposed relics in a site museum

Xilian Luo[a,b,*], Zhaolin Gu[a,b,*], Wei Tian[b,c], Yin Xia[d], Tao Ma[e]

[a] School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] Shaanxi Energy environmental & Building Energy Conservation Engineering Technology Research Center, Xi'an Jiaotong University, Xi'an 710049, China
[c] China United Northwest Institute for Engineering Design & Research Co., Ltd,No.81 Laodong Road, Xi'an, 710082, China
[d] Emperor Qinshihuang's Mausoleum Site Museum, Xi'an 710600, China
[e] Shaanxi Provincial Institute for the Conservation of Cultural Heritage, Xi'an 710075, China

ARTICLE INFO

Article history:
Received 30 June 2017
Received in revised form 1 December 2017
Accepted 1 December 2017
Available online 5 December 2017

Keywords:
Local ventilation system
Relic preservation
Energy saving
Site museum
Local environmental control

ABSTRACT

Indoor environmental controls are critical considerations when preserving artifacts in museums. Controlling the indoor environment of site museum buildings with large space layout typically consumes large amounts of energy. Most of the energy load needed to preserve relics is dissipated throughout the non-occupied space, because the environments that contain the relics occupy relatively little space compared to the entire exhibition hall. In this study, an energy efficient local ventilation system was proposed to independently control the environment of a funerary pit, which was preserved within a museum separate from the large exhibition hall. An experimental hall, which consists of a funerary pit and an experimental local ventilation system, was built to simulate a site museum building. Experiments were conducted to investigate the system's performance and to validate its ability to preserve historical terracotta figurines in their semi-exposed pits within the exhibition hall. The study evaluated the stability of the conservation environment and the system's energy usage by assessing the effects of the ventilation rate. The experimental results showed that the local ventilation system provides an energy-saving strategy supporting the environmental control of the funerary pit. The LV system significantly decreased temperature fluctuations in the funerary pit and temperature differences across semi-exposed relics. The system could be used to control the local preservation environment of the funerary pit separately from a large space exhibition hall.

1. Introduction

Energy consumption within buildings is responsible for 40% of the global energy requirement in the EU, the USA, and the UK [1–3], while it is responsible for more than one-third in China [4,5]. One-fifth of utilized energy in China is consumed by public buildings [5]. Fossil fuel depletion, growing energy demands from building users, and governmental policies for reducing environmental pollution emissions have increased the urgency for finding technological solutions to reduce energy consumption and increase energy efficiency. These solutions are particularly important for public buildings with high energy consumption, such as office buildings, schools, hotels, and museums [6,7].

China is an ancient civilized country with more than 4500 museums [8]; many of which are site museums, indicating that these museums are built directly at the place where the relics were found. Site museums preserve the original panorama of immovable historic sites in an exhibition hall, which generally means that most of the museum has a large open space layout [9]. However, this type of special building consumes significant amounts of energy for air conditioning (AC) systems, to create a stable and clean preservation microenvironment for the preservation of relics. Energy consumption in a museum building is typically of less importance in comparison to the demands of providing the appropriate preservation environment for collections [10]. However, wherever possible, energy use should be minimized, because cultural relics require a continuously working AC system throughout the year. This significantly increases the economic burden of the site museum's operational costs.

Given their significant energy consumption, more studies are required to fully understand microclimate control within site museums. Many recent studies have identified different ther-

* Corresponding authors at: School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an 710049, China
E-mail addresses: xlluo@mail.xjtu.edu.cn (X. Luo), guzhaoln@mail.xjtu.edu.cn (Z. Gu).

https://doi.org/10.1016/j.enbuild.2017.12.001
0378-7788/

mal requirements for artifact preservation compared to visitor comfort, concluding that both should be treated independently [11–14]. In general, environmental controls in visitor areas can be conveniently implemented using traditional central AC systems [15,16]. However, environmental controls for the preservation of unearthed relics remain a scientific and technological challenge, due to their stringent environmental requirements and unique preservation surroundings. Different requirements for visitor comfort and artifact preservation may cause museum staff to overlook the particular requirements of the relics. As a result, significant fluctuations can be observed in the indoor environment, i.e., the daily temperature fluctuations reach more than 10 °C in the Emperor Qin's Mausoleum Site Museum (China) and the Jinsha Site Museum (China) [17]. Many relics may suffer deterioration or ruin due to the adoption of improper preservation environments [18].

The Emperor Qin's Mausoleum Site Museum in Xi'an, China is a world-famous historical site, designated by United Nations Educational, Scientific, and Cultural Organization as one of the world's cultural legacies. To provide an energy efficient AC system that protects the immobile relics, the Ministry of Science and Technology of China approved a project for the development of an air curtain system and a capillary radiation cooling system. Research on these systems has generated promising results [12,14,19,20]. Both systems (air curtain and capillary radiation) have specific features that can create a steady preservation environment for the relics, allowing independent control and local preservation of artifact environments. However, both systems have limitations: The capillary radiation system belongs to an all-water AC system. The water pipeline for the chilled water is directly fixed in the preservation area, which causes the risks of water leakage within exhibition areas. Furthermore, the RH of the preservation area is typically very high, so that moisture easily condensates on the surface of water pipe and flows into the fragile earthen ruins. Moreover, the capillary radiant system may encourage fungal growth due to the beneficial high moisture, lack of air purification, and poor ventilation. The air curtain system belongs to an all-air AC system. The high air velocity at the jet outlet may cause vibration and noise. The symmetric arrangement of the jet outlet and return air grille of the air curtain system cause difficulties in the popularization of funerary pits with irregular geometrical structure.

By fixing both the air supply outlet and return air inlet at the bottom and top of the funerary pit, this study proposes an energy efficient local ventilation (LV) system to control the specific preservation environment for semi-exposed relics. This ventilation system is essentially a type of displacement ventilation without internal heat sources. Displacement ventilation systems are known to effectively control visitor-occupied environments in museums at a relatively low energy cost, and are therefore widely used in public buildings with large space layouts. DV systems can also improve the indoor air quality in occupied areas by separating contaminated air from clean air via stratification. The systems effectively achieve energy savings as well as high indoor air quality [21–23].

This research evaluated LV system performance when controlling the local preservation area in an experimental exhibition hall with a large space layout. The study specifically explored both the environmental stability and energy consumption of the LV system by evaluating the effects of the ventilation flow rate.

2. Preliminary energy consumption analysis and system description

China has many terracotta pottery relics; most of these have been unearthed and preserved in funerary pits. The Emperor Qin's Mausoleum Site Museum displays these types of relics, which are located in pits that form a reservoir at the ground of the exhibition hall (see Fig. 1a). This site museum generally faces the problem of either having no AC system, or having an AC system that wastes too much energy for cooling and heating the entire large space (see Fig. 1b). Efficient AC systems, such as stratified air conditioning and local heating systems are therefore attracting increased attention.

The total energy usage of a building's AC system (Q) can be estimated with Eq. (1).

$$Q = q_A A \tag{1}$$

In this expression, q_A represents the cooling load per unit floor area (*Q-Index*) and A represents the total air-conditioned area of the building. A site museum's exhibition hall generally has a high ceiling height (≥ 10 m), a large ratio of external building envelope area to wall area, large interior volumes, and complicated functions. A traditional central AC system that cools the entire space (see Fig. 1b) will be energy-hungry. The predicted cooling energy consumption and cooling load index of the No. 1 exhibition hall of the Emperor Qin's Mausoleum Site Museum would amount to 2860.66 kW and 179 W/m^2 [24,25]. In addition, an exhibition hall typically has a very large floor area (A), where only a small proportion is occupied by collections (see Fig. 1a). For example, at the Emperor's Mausoleum Site Museum, the area occupied by relics occupies only 34% of the total indoor space of the No. 1 pit exhibition hall [26]. This indicates that most of the energy load is likely wasted in areas that are not occupied by relics.

Eq. (1) highlights two ways to reduce the energy consumption: reducing the cooling load per unit area (q_A), or decreasing the air-conditioned area (A). The local environmental strategy achieves both; it reduces the height of the air-conditioned space to decrease q_A and provides local environmental control within the occupied area to decrease A. In general, it is difficult to implement a local heating in the funerary pit for this tall exhibition hall since hot air will rise up and move out of the funerary pit [12]. However, local cooling is particularly viable for the funerary pit because the soil temperature of the underlying funerary pit is typically lower (cooler) than the air temperature of the space above, once cool air is supplied to the pit, a steady thermal layer is created, which maintains a stable preservation environment (see Fig. 1c). This type of local cooling system is widely used in commercial buildings with large space layouts, including airport terminals, large conference halls, and large open plan offices. This further supports the successful implementation of independent controls for both the relic environment and the visitor environment [14].

3. Climatic recommendations for semi-exposed terracotta relics

The UNI 10829:1999 standard [27] indicates that terracotta relics are insensitive to ambient temperature and RH. Therefore, temperature and RH values are not provided as optimal conservation parameters, thus implying that environmental controls may not be necessary for terracotta relics in site museums. However, several studies have analyzed the primitive environments of relics in site museums, and recommended that environmental conditions should be reconsidered in a more differentiated and qualified way because these relics are semi-exposed complex (see Fig. 2) [20]. Environmental control systems are therefore required to reduce differences in temperature and RH between the surrounding soil and air, since a lack of equilibrium would cause fluctuations in environmental parameters and thus allow heat and moisture to transfer from the soil into the air [20,28].

In general, the soil environment underneath the relics is more stable than the air environment. As such, the natural soil parameters should be considered as the target values for relic conservation. The soil temperature at depths of less than 10 m below the ground