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Reduced-scale experimental model and numerical investigations to buoyance-driven natural ventilation in a large space building

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ABSTRACT

This research establishes a reliable and effective methodology for evaluating the buoyancy-driven ventilation performance in a large space building through a reduced-scale experimental model and full-scale prototype numerical simulation. The measured values are modeled back to the corresponding environmental parameters for the prototype building by using similarity analysis. The experimental data are compared with numerical simulation results, and good agreements with relative errors no more than 1% in temperatures and airflow rates are achieved. The thermal comfort conditions in the building are numerically investigated in terms of well-known thermal comfort index. Results indicate that pure buoyancy-driven ventilation cannot keep people thermally comfortable when the ambient temperature is high, and mechanical ventilation is needed for such a building with a large glass ceiling. The proposed methodology provides a useful procedure to quantify the thermal conditions in such a large space building with a semi-transparent glazed ceiling, and the results of this study can be considered at the initial design stage of the building to obtain a comfortable indoor thermal environment.

1. Introduction

An increasing number of large space buildings have recently emerged worldwide, and the indoor thermal environment of these large space buildings has received considerable emphasis. The heating, ventilation, and air conditioning (HVAC) generally comprise 50%–60% of the total building energy consumption according to the annual review by the U.S. Department of Energy [1]. A growing consensus regarding natural ventilation, as a non-energy consuming method, is a key component in the mix of solutions to maintain satisfactory indoor air quality and thermal comfort for large space building in an energy efficient way [2]. Detailed knowledge of the indoor air temperature, ventilation rate, and thermal comfort index is important to gain insight into the design principle of such low-energy large space buildings. There are a number of methods available for the evaluation of the natural ventilation performance, each having their own advantages and limitations [3].

Site measurements on indoor thermal environments in full-scale buildings have been performed in many studies [4–9]. However, this approach is challenging because outdoor environmental conditions are usually complicated, constantly changing, and uncontrollable in field measurements of the prototype building [10], especially for pure-buoyancy driven natural ventilation. In addition, the indoor thermal environment is essential for determining the acceptable thermal environmental parameters during the initial building design stage. The designer needs direct, accurate, and available data of the natural ventilation performance to ensure a proper design. Given that conducting full-scale experiments is generally expensive and time-consuming, setting up small-scale experimental models in a controlled chamber will help overcome this problem. Linden et al. conducted several key studies on small-scale experiments to provide an insight into the fluid dynamics of ventilation flow in a room, in which water was used as the working fluid and buoyancy force was produced by salinity differences [11]. Gladstone and Woods also utilized water as working fluid in their small-scale analog laboratory experiments, in which buoyancy force was generated through an applied heat flux on the floor of the experimental model [12]. Walker et al. analyzed similarities of a reduced-scale experimental model employing air as the working fluid for buoyancy-driven natural ventilation, in which the buoyancy forces were created by simulating the internal loads of the building by using several heaters [13].

Apart from small-scale experimental methods, computational fluid dynamics (CFD) is another cost-effective and easy way to investigate

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the effect of natural ventilation on the indoor environment of a building [14]. Given that CFD can provide detailed spatial information on values for variables, such as air temperature, pressure, and velocity, throughout the entire flow domain, CFD techniques are increasingly being employed to predict building airflows and test natural ventilation strategies, especially for a few complicated geometries and situations [15–17]. CFD simulations have been benchmarked against experimental measurements by many researchers [6,18–20]. Lau and Chen conducted a numerical investigation on the performance of floor-supply displacement ventilation with swirl diffusers or perforated panels under a high cooling load [21]. Shafqat and Patrick used CFD to investigate solar-assisted buoyancy natural ventilation in a simple atrium building at the initial design stage, and the effects of different design parameters on the thermal conditions in the building were examined [22]. Espinosa and Glicksman performed numerical simulations on a typical occupied office to investigate the effects of ventilation parameters on the thermal stratification in the space, in which the ceiling was treated as heat flux boundary condition to represent the heat gains in the room [23]. A limited number of CFD studies were found on the natural ventilation performance in the large space building with a semi-transparent glazed ceiling, for which the main heat load is the external solar radiation. Given that CFD models often require approximation and simplification which lead to uncertainties to some extent, CFD methods are often applied together with experimental methods to provide reliable and detailed information on ventilation performance [24].

This study was undertaken to evaluate the indoor thermal environment in a large space building. A glazed ceiling is incorporated into the design of the large space building to take advantage of daylighting, solar heating, and buoyancy-driven natural ventilation [25]. The escaping air through upper openings of the glazed ceiling can take heat out, thereby improving the indoor thermal environment. Given that evaluating the thermal environment inside the building under natural ventilation condition is the key to designing an air-conditioning system in large spaces with better thermal and energy-saving performance, experiments are performed on a reduced-scale building model. By using the similarity analysis, the experimental results from the reduced-scale model can be scaled back to corresponding environmental parameters for the prototype building. Unlike previous small-scale experimental studies in which heat sources in the building are treated to be localized or evenly distributed at floor level by using heaters, this study applies artificial environment simulation technology in a small-scale experiment.

An artificial environment simulation laboratory (AESL) was constructed to achieve active control of environmental parameters. The artificial environment simulation can replicate the needed solar radiation and ambient temperature, thereby speeding up the experimental process and ensuring convenient measurement [26]. One of the most famous artificial environment simulation laboratories is Biosphere 2, which was supposed to test whether humans can thrive in a closed replicated mini-ecosystem [27]. CFD technology is also adopted in this study to calculate the temperature distribution, buoyancy natural ventilation, and thermal comfort in the large space building. Given the large glass ceiling of the building, solar load model and two-band discrete ordinate (DO) radiation model are adopted in the numerical simulation to consider the greenhouse effect due to the semi-transparent glass ceiling.

2. Artificial environment simulation lab

An AESL was built to artificially replicate the environment conditions, as shown in Fig. 1. The dimensions of the laboratory are 6.95 m (W) × 10.28 m (L) × 4.8 m (H). The control room is located on the second floor, where computers, operation switches, and corresponding frequency converters are installed. The internal wall of the control room has a viewing window to allow observation of the experiment inside the testing area. Solar simulator and temperature control system are installed to achieve active control of the indoor temperatures and radiation intensity, respectively, and will be described in the following sections.

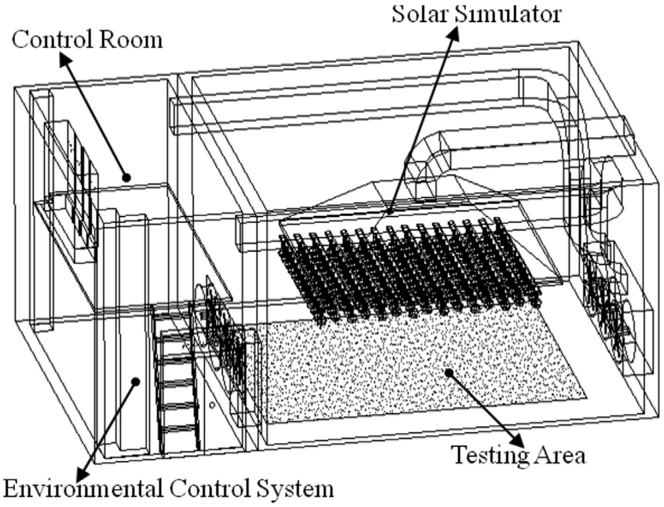

Fig. 1. Schematic of the AESL.

2.1. Solar simulator

A 400 W metal halide gas discharge lamp is selected as the light source for the solar simulator to achieve a spectral output similar to natural sunlight [28]. A total of 188 lamps are mounted on a height-adjustable steel frame and arranged in a quincuncial distribution to achieve uniform irradiance distribution on the testing area, as shown in Fig. 2. The 188 lamps are divided into four groups, (namely, A, B, C, and D), and can be operated individually or in combination. Hence, the radiation intensity of the solar simulator can be continuously adjusted from 150 W/m^2 to 1000 W/m^2 through a combination of different lamp groups and height adjustments of the lamp array.

2.2. Temperature control system

Fig. 3 shows a schematic of the temperature control system in the AESL. A set of refrigeration equipment was installed to provide the necessary cooling for temperature control, and three groups of heaters were adopted to heat the air. Six axial fans were controlled by variable-frequency drive system to achieve fine adjustment of the indoor temperature. A forced air cooling system is constructed on top of the lamp array to remove the heat generated by the lamps. All equipment is controlled through the computer and programmable logic controller to achieve a control precision of ± 0.5 °C.

2.3. Similarity design of the AESL

Similarity problems between prototype and experimental model are the key issues of the model experimental study on the natural ventilation of the large space building. In other words, determining the relations between the reduced scale of the geometry (C_L) and those of the measured parameters (velocity C_u and temperature rise C_T) is necessary. The reduced scale can be obtained from the dimensional analysis of a simplified form of the Navier-Stokes equation for natural convection problem:

$$u\frac{\partial u}{\partial x} = g\theta\beta + \nu\frac{\partial^2 u}{\partial x^2} \tag{1}$$

where θ is the temperature difference from the reference temperature, β is the thermal expansion coefficient. Substituting the dimensionless factors $x^* = x/L$, $u^* = u/u_0$, and $\theta^* = \theta/\Delta T$ into Eq. (1):