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Design optimization and field demonstration of natural ventilation for high-rise residential buildings

Chaobin Zhou [a,b], Zhiqiang Wang [a,c,*], Qingyan Chen [a,d], Yi Jiang [e], Jingjing Pei [a]

[a] School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
[b] China Vanke Co., Ltd., Chengdu Regional Headquarters, Chengdu 610066, China
[c] Built Environment Group Ltd., Tianjin 300072, China
[d] School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, USA
[e] Nanchang University, Nanchang, China

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ABSTRACT

Natural ventilation in residential buildings has a great potential for conserving energy and improving the health of occupants. This paper first presents a design strategy for optimizing natural ventilation in high-rise residential buildings in Chongqing, China, a region with unfavorably low wind speed. Through the use of CFD modeling, building orientation and spacing were adjusted, wind paths were created into internal zones, and two windows were constructed in each bedroom. The optimized design reduced the age of air to less than 6 min in 90% of the rooms, as compared to an age of greater than 30 min in 50% of the rooms in a conventional design. Natural ventilation was found to be effective in the Chongqing area with the optimized design. This investigation also measured the local age of air and air change rate in a building with the optimized design using a tracer-gas method. The measurements confirmed the reliability of the CFD results.

1. Introduction

In China, residential buildings consumed 345.58 million tons of standard coal in 2010. Together these buildings were the second largest energy user in the nation, accounting for 10.6% of total primary energy consumption [1,2]. In many regions of China, natural ventilation could be used to reduce energy use in residential buildings by up to 40% as compared to that in air-conditioned buildings [3–5]. Natural ventilation can also improve indoor air quality (IAQ) because of the large amount of outdoor air used, and it requires minimal maintenance, in contrast to mechanical ventilation. Therefore, it is important to study natural ventilation in residential buildings in order to maximize its benefits.

The beginnings of natural ventilation design can perhaps be considered as the time when these human-occupied enclosures started to become purpose-built. Evidence of purpose-built ventilation in China can date back to the Neolithic period [6]. Early designs were primarily empirical and evolved from experience. Natural ventilation design today makes much more use of theoretical modeling, supported by experimental (laboratory and field) measurements. The principal factors affecting natural air movement around and within buildings include: (1) the site and local landscaping features; (2) the building shape and building envelope design; (3) the internal planning and room design [7]. Naturally ventilated buildings should be oriented to maximize their exposure to the required (summer) wind direction, and designed with a relatively narrow plan form to facilitate the passage of air through the building (cross ventilation). The variety and diversity of purpose-provided natural ventilation systems that have been proposed in recent years is staggering [8–11]. These systems are invariably conceived as variants of three fundamental approaches to natural ventilation, including wind-driven cross ventilation, buoyancy-driven stack ventilation, and single-sided ventilation. Haves et al. described the design of a building including the use of both coupled thermal and airflow multi-zone and computational fluid dynamics simulations performed. The strategy employed was a wind-driven cross ventilation flow through a narrow, open office floor plan in a high-rise tower [12]. Wang et al. [13] pointed out that naturally ventilated building design in hot-humid climates needs to pay more attention to orientations, shading devices, material selections, and window sizes [13]. Most of current studies focused on the overall design strategies for non-domestic buildings or low-rise residential

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[*] Corresponding author at: Corresponding author at: Tianjin University, Built Environment Group Ltd., Tianjin, School of Environmental Science and Engineering, Tianjin 300072, China. Tel.: +86 13512830852.
E-mail address: zqwang@tju.edu.cn (Z. Wang).

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buildings, while very limited studies were found regarding to the detailed design procedure for optimizing the natural ventilation of high-density and high-rise residential buildings.

Use of natural ventilation in China is challenging because of the rapid rate of urbanization, with a trend toward high-density and high-rise residential buildings. There are typically 10–15 housing units per floor, and there is one exterior window for most of the rooms in these units. In addition, high-rise residential buildings in China present unique IAQ problems that result from the Chinese style of cooking. Cooking and winter heating are responsible for much of the overall air pollution in dwellings [14–16]. The pollutants in a contained micro-environment such as a building have a great impact on occupants' health [17–20]. Because few Chinese high-rise residential buildings have mechanical ventilation, it is essential to design buildings with natural ventilation in order to improve IAQ.

Many Chinese cities are located in climates that may not seem suitable for natural ventilation. For example, the city of Chongqing is in a subtropical zone with a moist monsoon climate. It is hot and stuffy in summer, and gloomy and cold in winter. The average wind speed is only 1.4 m/s [21]. Nevertheless, when Li et al. [22] conducted a survey and tested the indoor thermal environment of residential buildings in Chongqing, they found that natural ventilation was a cost-effective way to improve this environment. Residents of Chongqing are accustomed to opening windows for natural ventilation at night. However, in a 2007 survey Shen et al. [23] found that 60% of residential buildings had no cross-ventilation capacity. This finding implies that most of the buildings in Chongqing were not designed for natural ventilation. The lifestyle of Chongqing residents, along with their desire to improve IAQ and thermal comfort and reduce energy use, suggests a need to re-examine the use of natural ventilation in residential buildings.

This paper presents our study of the optimization of natural-ventilation design for a high-rise residential complex in the Chongqing region. It provides an idea of building slotted residential tower building and constructing two orthogonal exterior windows in each bedroom to solve the lack of natural ventilation for the high-rise and high-density residential buildings in Chongqing, China. The ventilation performance of the complex was validated by on-site measurements.

2. Methodology

2.1. Design optimization procedure

Many studies [24–27] have concluded that passive building design is the most economical and effective strategy for reducing thermal load in residential buildings. Buildings with passive designs, including natural ventilation, passive solar energy applications, thermal mass, etc., can reduce total energy consumption by more than 50% [28]. Building design with natural ventilation involves multiple factors, such as local weather conditions (wind speed and wind direction), building arrangement (building shape, spacing, and orientation), and floor planning (floor partition, window location, window size, etc.). The design may also need to account for unpredictable variables such as occupant behavior. These factors can generally be classified into two groups: controllable and uncontrollable factors. Examples of uncontrollable factors are the local climate and geographical conditions, occupants' behavior, customized room furnishing, and partition design. Controllable factors, those that can be specially designed and optimized, are the focus of the current study. Our optimal design for natural ventilation consists of a three-stage procedure, as shown in Fig. 1: (1) building-orientation optimization at the community level, (2) wind-path design at the floor-plan level, and (3) fenestration design at the room level.

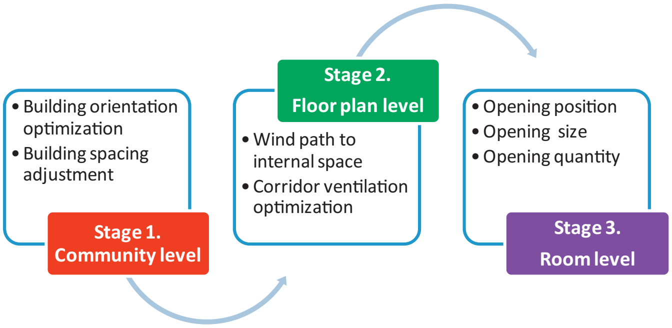

Fig. 1. Three-stage design optimization procedure.

A number of numerical tools are available for optimizing natural ventilation design, such as computational fluid dynamics (CFD) models [29–32], multi-zone network models [33–35], zonal models [36–39], etc. CFD models are the most advanced and accurate, although their computing time is high and the required inputs are very detailed. Because optimization is a very specialized procedure and accuracy is one of the primary concerns, this investigation used a CFD model. A commercial software program, ANSYS Fluent 12.1 [40], was used to simulate the air velocity and pressure field in and around buildings for a number of different design cases. The pressure difference between the windward side and leeward side was used to evaluate the performance of natural ventilation. A detailed description of the CFD simulations can be found in Liu et al. [41].

2.2. Field measurements

CFD simulations can provide very detailed three-dimensional information about airflow and pressure distributions in and around a building. For evaluation of the natural ventilation performance of a building, however, on-site measurements of the distributions are not feasible. Since the age of air and air change rate are the most critical parameters for evaluating natural ventilation design [42–44], this investigation used these two parameters as performance criteria. It was possible to measure them on site.

There are essentially two methods for determining age of air and air change rate in field tests [6]. The first method uses a tracer gas to determine the age of air and air change rate according to the principle of mass conservation. The second method is to directly measure the air change rate through individual openings. With natural ventilation, the variation in air velocity (magnitude and direction) with time is likely to be great, and flow through openings is not always unidirectional. Therefore, the tracer-gas method would provide more accurate results. This method has three established approaches, namely, the decay, constant concentration, and constant emission methods. The decay method is the simplest one, primarily because knowledge of the amount of gas injected is not required. In the decay method, the tracer-gas concentration is initially brought to a suitable level, and the concentration decay is then measured with respect to time. This investigation selected the decay method.

Age of air and air change rate are related to meteorological parameters, such as wind direction and speed around the building. This investigation used a HOBO-U30 weather station to obtain meteorological data. The weather station was located on the rooftop of the test building. Table 1 shows detailed information for the instruments used. Because the buildings were still under construction when the tests were performed, and the wall insulation had not been finished yet, therefore the indoor thermal environment was not monitored. Also as the rooms were not occupied yet,