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Design Optimization and Field Demonstration of Natural Ventilation for High-Rise Residential Buildings

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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 minutes in 90% of the rooms, as compared to an age of greater than 30 minutes 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.

Key words

Natural ventilation; Residential buildings; Design optimization; Field measurements; Age of air; Air change rate

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]. 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. (2003) 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. (2006) 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 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 Figure 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.

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, the field measurements only focus on the age of air and ventilation rate. Since the tested building was not completed finished when the tests were conducted, all openings such as windows and doors were not properly placed. To mimic the real windows and doors, the openings were sealed by wood board on site. 30% of sealed area for the windows can be opened.

This investigation used carbon dioxide (CO_2) as the tracer gas, because it is inexpensive, can be easily measured, and does not constitute a health hazard to the researchers. However, as the CO_2 concentration in the atmosphere is rather high and can fluctuate, it was necessary to measure the background concentration during the field tests. In addition, since the CO_2 breathed out by building occupants can affect measurement accuracy, it should be used as a tracer gas only in unoccupied spaces. This study released CO_2 into unoccupied test rooms.

Tracer-gas concentration in the test rooms was measured using the set-up shown in Figure 2. One sampling point (Point 1) was located in the center of the room at a height of 1.5 m above the floor, and the other (Point 2) was close to the headboard of the bed, at a distance of 0.5 m from the wall and a height of 1 m above the floor.

The measurement procedure was as follows:

1) Close the windows of the test room (which means 100% of the window opening were sealed by wood board) ;
2) Release CO_2 into the bedroom and turn on the fans to mix the tracer gas with the room air;
3) Stop CO_2 injection when the CO_2 concentration in the room has reached 4000 ppm. Shut off the two mixing fans after five minutes;
4) Open the windows to allow fresh air from outdoors to enter the bedroom by means of natural ventilation (which means 30% openable area in the sealed window was opened);
5) Measure the CO_2 concentration continuously at the two sampling locations; and
6) Complete the measurement when the CO_2 concentration has decayed to the background level.
7) Repeat each measurement two times to ensure data quality.

2.3 Calculation of ventilation rate

Note that the tracer-gas decay technique measures concentration in an enclosed space, rather than directly measuring the age of air and air change rates. However, the tracer-gas concentration can be used to calculate the age of air and air change rate by means of the following mass balance equation for an enclosed space:

$$V\frac{dC(t)}{dt}=F(t)-q(t)C(t) \tag{1}$$

where V is the volume of the enclosed space, m^3; C is the tracer-gas concentration in the enclosed space, $m^3{}_{CO2}/m^3{}_{air}$; q is the ventilation rate, $m^3{}_{air}/s$; and F is the tracer-gas release rate, $m^3{}_{CO2}/s$. In the decay method, no tracer gas is released during the measurement, so F(t) = 0 in Equation (1). The local age of air can be calculated as follows:

$$\tau_i = \frac{\int_0^\infty C_i(t)dt}{C_i(0)} \qquad (2)$$

where τ_i is the age of air at the measurement location, s; $C_i(0)$ is the local tracer-gas concentration at t = 0, ppm; and $C_i(t)$ is the tracer-gas concentration at time t, ppm.

In this study, the air change rate in an enclosed space is defined as the flow rate of outdoor air into the space divided by the volume of the space. With the decay method, the air change rate can be obtained by:

$$C_t = C_0 e^{-Nt} \qquad (3)$$

where N is the air change rate, h^{-1}; C_t is the concentration of tracer gas at time t, ppm; C_0 is the tracer-gas concentration at t = 0, ppm; and t is the testing time, s.

2.4 Ventilation requirements

For the sake of occupants' health and comfort, the ventilation rate should meet the requirements listed in Table 2. China's national standard for residential buildings [38] requires 0.4-0.7 air changes per hour (ACH). If the living-space area is less than 10 m^2/person, the ventilation rate should be not less than 0.7 ACH; if living space is 10-50 m^2/person, the rate should be 0.4-0.7 ACH; and if living space is greater than 50 m^2/person, the rate should be not less than 0.4 ACH. The latest ASHRAE standard [39] requirement for fresh air is calculated as the sum of two parts: 2.5 L of fresh air per second per person plus 0.3 L of fresh air per second per m^2 construction area. CIBSE Guide A [40] requires a rate of 0.4-1 ACH. Overall, the required ventilation rate for common residential buildings is 0.4-1 ACH. In order to meet the requirements for different situations, one (1) ACH was used as the criterion to evaluate the optimization design in this study. This means that if the ACH is lower than 1 or the corresponding mean age of air is greater than 60 minutes, the natural ventilation performance is considered to be poor.

3. Results and Discussion

The design optimization procedure and ventilation measurement method described in Section 2 were applied to a residential community in Chongqing. The community constituted of six buildings, as shown in Figure 3(a), with a total floor area of 300,000 m^2 and a total plot area of 50,000 m^2. Buildings 1-3 each had 26 floors with a floor height of 2.95 m. Buildings 4-6 each had 33 floors with a floor height of 2.85 m. The construction area on each floor of the tested building was 746 m^2, as shown in Fig. 3(b), and it was partitioned to form three types of units: four units with an area of 85 m^2 each (Unit A), four with an area 67 m^2 each (Unit B), and two with an area of 70 m^2 each (Unit C). Five of the ten units on the fifth floor of Building 1, Units A2, A4, B2, B4, and C2, were selected as the test units in this investigation.

3.1 Optimized natural ventilation design

3.1.1 Stage 1: optimization at the community level

In the three-stage strategy, building orientation is the most important factor for optimization. Naturally ventilated buildings should be oriented to maximize their exposure to the dominant wind direction. The building design should also have a relatively narrow span to facilitate the passage of air through the building via cross ventilation.

Our previous study addressed the effects of building distance and orientation on natural ventilation in Chongqing [41]. The effect of building spacing and orientation was investigated through the analysis of air velocity field and wind pressure field around buildings by computational fluid dynamics method. The natural ventilation potential increases with an increase in the distance between buildings and a decrease in the angle between a building and the wind direction. It was showed that the pressure difference between buildings increased by 20% and the pressure difference between units increased by 25% when the distance between buildings increases from 28 m to 34 m. Further analysis showed that the pressure difference between buildings increased by 13% and the pressure difference between units increased by 27% with the change of building orientation from the base case to the optimized case if the space between the buildings remained the same as 34 m. The base case means without rotation for all the six buildings. The optimized case means when the orientation was 37° north by west for buildings 1, 2, and 3 and 25° north by west for buildings 4, 5, and 6**.** Taking into account building distance and orientation as well as the actual topography of the site, the study obtained an optimal building layout for the community. The same layout was used in the current study. Further details of the optimization process can be found in our previous study [41].

3.1.2 Stage 2: optimization at the floor-plan level

After the building orientation and spacing had been determined, the optimized floor plan was obtained through CFD simulations of the age of air. A user-defined function (UDF) in the ANSYS Fluent software was used to compute the age of air at the floor-plan level. The building floor plan was optimized to draw more wind into the interior zones and thus reduce the age of air.

High-rise residential buildings in China have typically been constructed as square or rectangular structures, which do not facilitate the flow of outside air into interior zone. Therefore, one wind path in the north-south direction and two in the east-west direction (as indicated by the arrows in Fig. 4) were designed to introduce air to those rooms which did not originally have windows directly facing the wind direction. The dimensions of the wind paths are also shown in Figure 4.

To verify the effectiveness of this design, we further compared the age of air in four different cases with and without various wind-path designs. The boundary conditions in the simulations were the dominant wind direction (northwest) and yearly average wind speed (1.4 m/s) in Chongqing. In a typical high-rise residential building without internal wind paths, the age of air in most of the internal zones was greater than 10 minutes, as shown in Figure 5(a). To improve the ventilation rate in the internal zones, a vertical wind path was created, and the age of air was simulated as shown in Figure 5(b). Ventilation in the internal corridors, and therefore in the neighboring rooms, was improved, but there were still some poorly ventilated rooms on the leeward side. With two horizontal wind paths as shown in Figure 5(c), the floor area with age of air greater than 10 minutes was further reduced. Figure 5(d) shows the age of air with one vertical and two horizontal wind paths. The age of air in 90% of the rooms was less than five minutes, indicating an even distribution of outdoor fresh air in the building, and therefore an optimal floor design was achieved. Note that the highest age of air in these four cases was only about 10 minutes, which was already far lower than the criterion of 60 minutes for acceptable ventilation described in Section 2.4. That standard was created to regulate the minimum ventilation flow rate for mechanical ventilation rather than natural ventilation.

3.1.3 Stage 3: optimization at the room level

With the creation of wind paths in the building floor plan, it became possible for all rooms to have at least one exterior window directly exposed to outdoor air, as shown in Figure 4. Most of the bedrooms had two orthogonal exterior windows. All the internal doors were open and the external windows were half open, while the exterior doors were closed. When the exterior windows were open, outdoor air could penetrate into the bedrooms even if the bedroom doors were closed.

3.1.4 Comparison of the optimized ventilation performance with ventilation in conventional high-rise residential buildings

To validate the three-stage optimization design, two similar high-rise residential buildings of conventional design were selected for comparison. One building consisted of 30 floors, with 10 units on a standard floor; the other consisted of 26 floors, with 12 units on a standard floor. There were no wind paths to the internal zones, and the bedrooms each had only one window. All the internal doors were open and the external windows were half open, while the exterior doors were closed. The same weather conditions as the optimized building were used in the simulations for the conventional buildings.

The simulation results are shown in Figure 6. In the optimized building, the age of air on the windward side was less than 3 minutes (Fig. 6(a), where arrows indicate the wind paths). The internal zones, including the corridors, had an age of air less than 5 minutes. The leeward units had an age of air between 5 and 10 minutes, except for the room in the corner. The age of air was far below the criterion used in this study, which is 60 minutes (a value based on the minimum required air change rate).

In Conventional Building 1, the age of air on the windward side was less than 10 minutes, and on the leeward side it was between 30 and 60 minutes (Fig. 6(b)). The internal zones may have had an age of air greater than 60 minutes. Although the design just met the national standard, it was far worse than the optimized design. The age of air in Conventional Building 2 (Fig. 6(c)) was slightly less than that in Conventional Building 1 because of a difference in design layout. Our investigation shows that natural ventilation could be effective in the Chongqing area, despite the seemingly unfavorable climate conditions.

3.2 Validation of the design by field measurements

In order to validate the above numerical simulation, we conducted field measurements of the age of air and air change rate in one of the conventional buildings in Chongqing. The field measurement is only for a fixed testing condition, which was conducted in September. Because of operational limitations, the measurements were conducted on the nineteenth floor of Building 1 (a 26-story building) and in the bedrooms of Units A2, A4, B2, and C2 (a total of seven rooms). In each room, the tests were repeated three times for the same wind direction. The outdoor CO_2 concentrations were measured for all the tests. The outdoor CO_2 concentrations during the test period were in the range of 356-667 ppm, and with an average of 430 ppm.

Table 3 shows the measured local age of air in the primary bedrooms (PB) and secondary bedrooms (SB). The wind speed and direction were obtained from the weather station and these measurements confirmed that the wind speed was fairly low, even though the weather station was located on the rooftop of the building (26 floors above street level). The measured age of air in 80% of the test units was less than 5 minutes. The measured age of air in the primary bedroom in Unit B2 was in the range of 14-20 minutes, which was greater than that in the other rooms because this unit had only one window.

Because the previous simulation was carried out for the fifth floor during the design stage, a simulation for the nineteenth floor was conducted to provide a more accurate comparison with the measured results. The actual measured wind direction and speed were used as boundary conditions, as listed in Table 3. The average wind velocity for the three repeated tests was used in the simulation. Because the weather station was located on the rooftop of Building 1 and the field measurements were conducted on the nineteenth floor, this investigation estimated the corresponding wind velocity on the nineteenth floor as follows. Because wind velocity increases with the height of the building, the relationship between wind velocity and height can be expressed by the following empirical equation [48]:

$$v = v_1 \left(\frac{h}{h_1} \right)^{0.33} \tag{4}$$

where v is the wind velocity at height h, m/s; v_1 is the wind velocity at height h_1, m/s; and h is the height of the building, m. Agreement between the measured average age of air and the simulated results is fairly good, as shown in Table 3, although the experimental data was quite different among the three tests.

Figures 7 and 8 further compare the age of air at Sampling Points 1 and 2 for the seven cases. The simulation results again agree well with the measured data in all cases except Cases 4 and 5. The measured wind directions listed in Table 3 were the dominant wind directions during the measurements. In Case 4, the dominant wind direction was northwest for only 60% of the time; for 25% of the time, the wind direction was west, and the air could travel along the horizontal wind path to enter the secondary bedroom in Unit A4 through the exterior window. However, such a situation could not be captured by the simulation using the northwest wind direction as the boundary condition. Therefore, the measured age of air in Case 4 was less than the simulated age. This explanation can also be applied to the difference observed for Point 1 in Case 5.

In Case 5, because the primary bedroom in Unit B2 had only one exterior window, the age of air was naturally greater than that for the other rooms. Overall, the measured data agrees well with the simulated results, thus validating the effectiveness of the CFD-based design optimization used in this study.

This study also conducted tests of air change rate of the secondary bedroom of unit A2, B2, and B4. The test was repeated for three times. Table 4 listed the test result. It shows that the air change rate for these three rooms were in the range of 9-12 h^{-1}. The measured results validate the CFD simulated results well. Moreover, because the measurement in this study was conducted with door of bedroom closed, the real natural ventilation rate will be further enhanced if the door is opened.

The indoor thermal conditions were not monitored due to the limitation of the on-site conditions. This investigation did not study discomfort hours. However, our previous study [41] analyzed comfort hours by EnergyPlus simulations by showing the indoor comfort hours and percentage of comfort hour for each month with only natural ventilation. It indicated that spring (March, April, May) and autumn

(September, October, November) had the highest comfort hours. The comfort percentages in May and September were over 60%. The comfort percentages in March and November were around 10%. The investigation also showed a potential to use natural ventilation in hot summer. The comfort percentages in July and August could be around 30%.

4. Conclusion

A three-stage design optimization strategy, consisting of the community layout level, floor plan level, and room design level, was developed and applied to optimize natural ventilation performance in high-rise residential buildings. The optimization adjusted building orientation and spacing at the community level, created wind paths at the floor level, and optimized fenestration at the room level. Numerical simulations of the age of air and air change rate in the rooms by computation fluid dynamics showed that the optimization can effectively improve natural ventilation.

The optimized design was confirmed by comparing its ventilation performance with that in conventional designs, using CFD simulations. The design analysis was performed for high-rise buildings in Chongqing, China, where the climate is generally regarded as unfavorable for natural ventilation. In the optimized design, the age of air on a standard floor was less than 6 minutes in 90% of the rooms, whereas it was greater than 30 minutes in 50% of the rooms with the conventional design. The results indicate that natural ventilation can and should be used in residential buildings in the Chongqing area.

This investigation conducted field measurements of natural ventilation performance in the optimized building to validate the three-stage design optimization. The measured age of air in most of the rooms was less than 10 minutes. The measured data agrees well with the simulated results, thus validating the effectiveness of CFD-based design optimization.

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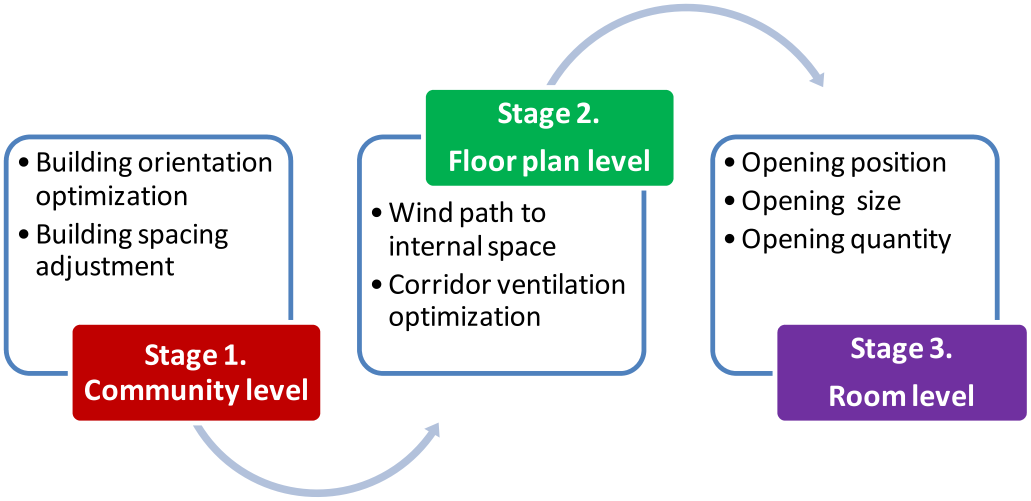

Fig.1 Three-stage design optimization procedure

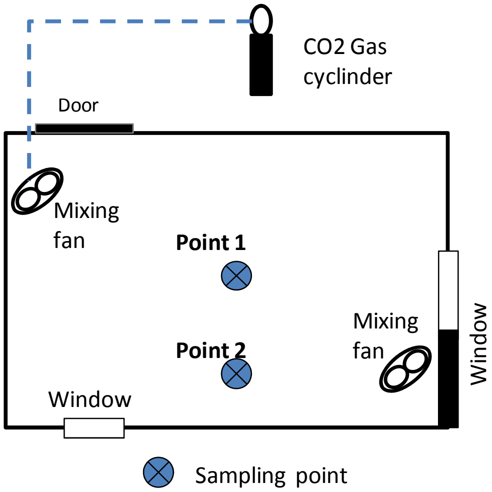

Fig. 2 Tracer-gas sampling set-up for field measurements

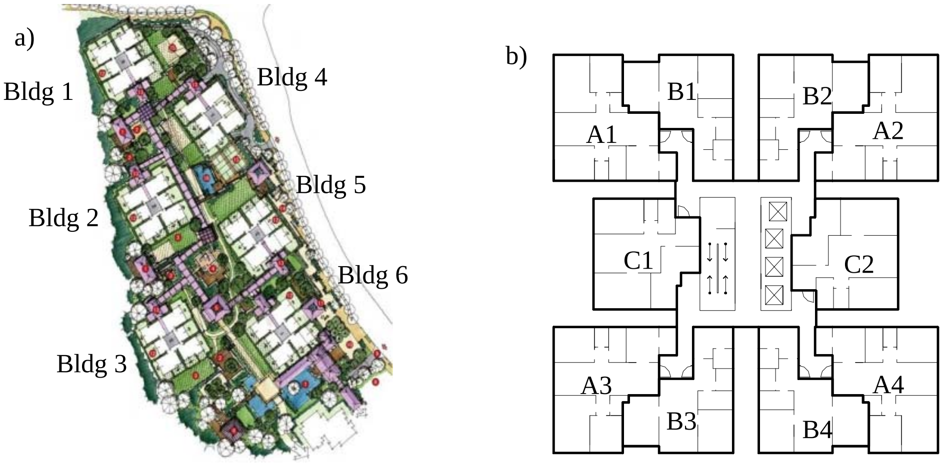

Fig.3 (a) Residential community with six buildings and (b) standard floor plan

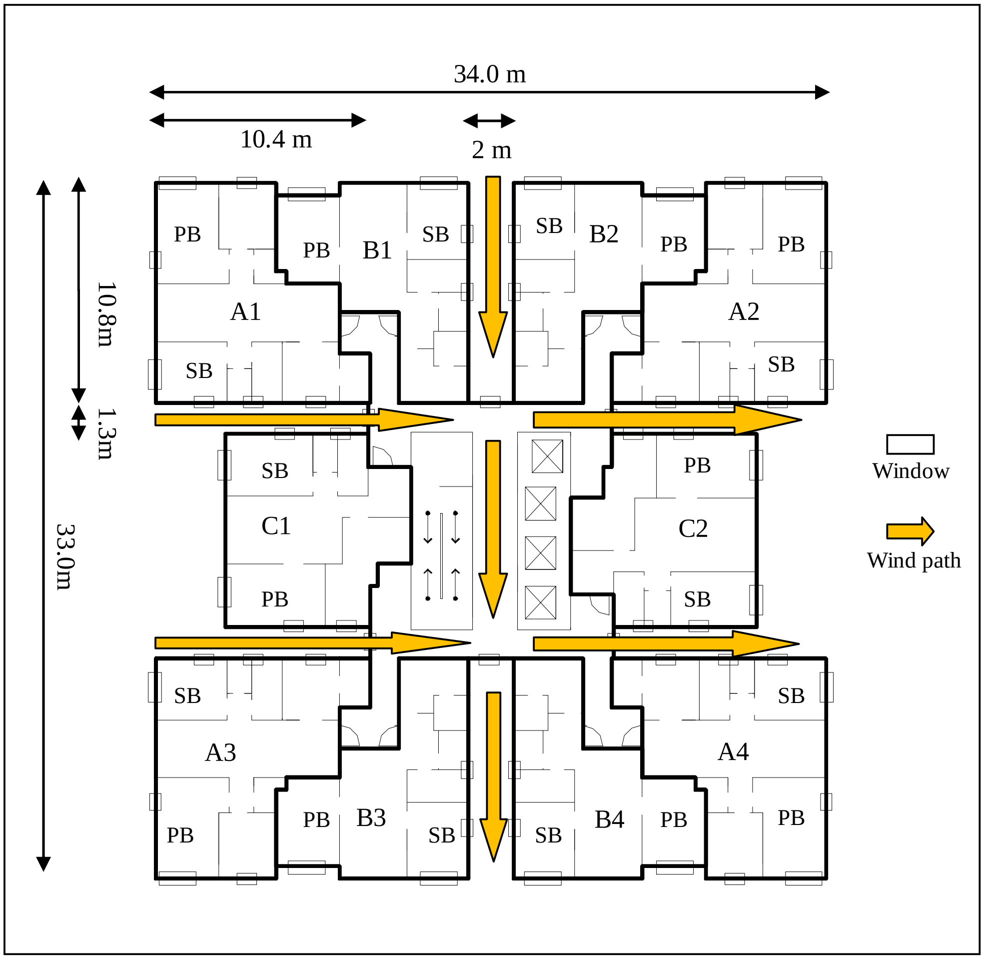

Fig. 4 Creation of wind paths in the floor plan to provide exterior windows for all rooms

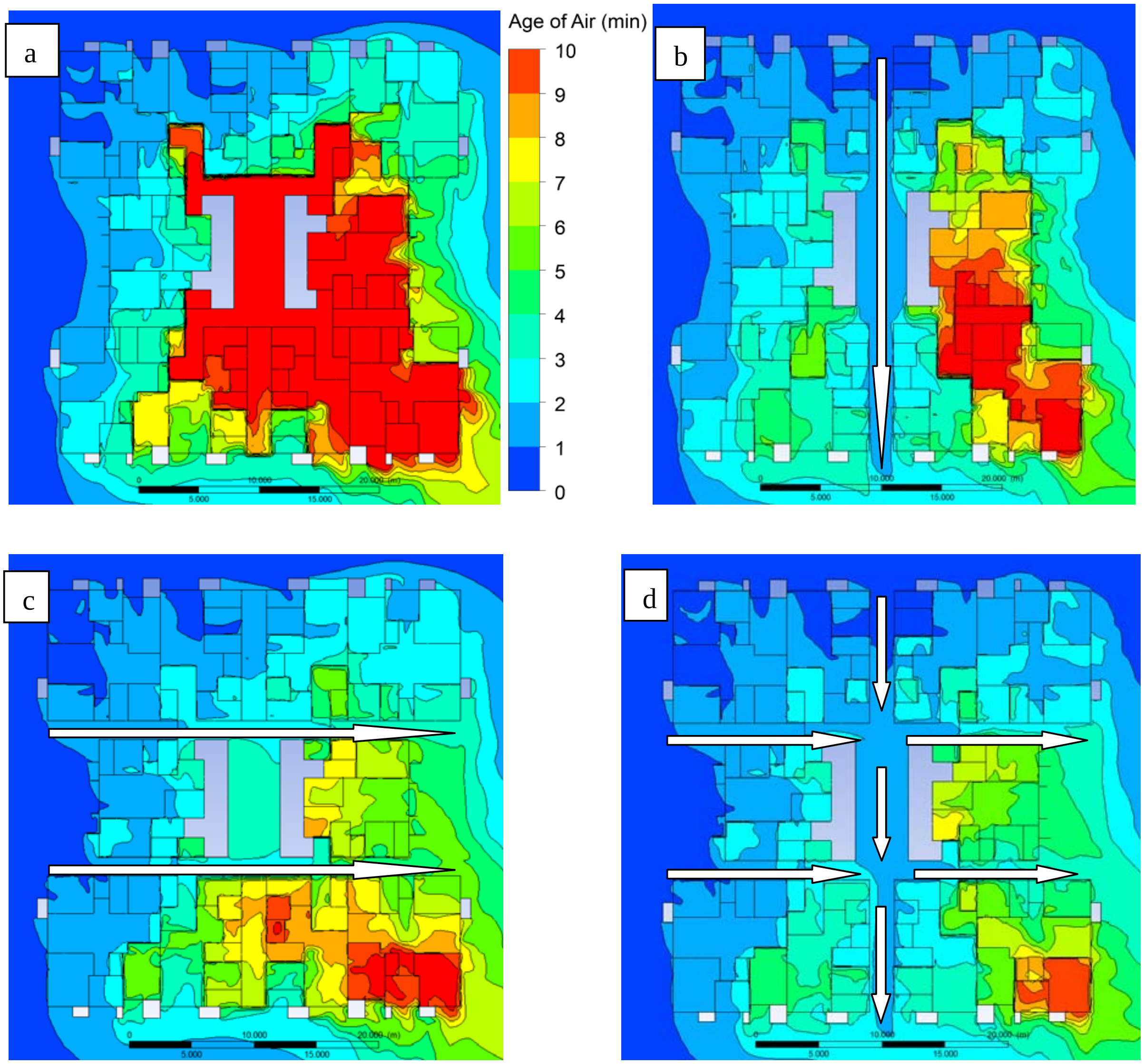

Fig. 5 Simulated age of air at different conditions: (a) without wind paths; (b) with one vertical wind path; (c) with two horizontal wind paths; and (d) with one vertical and two horizontal wind paths

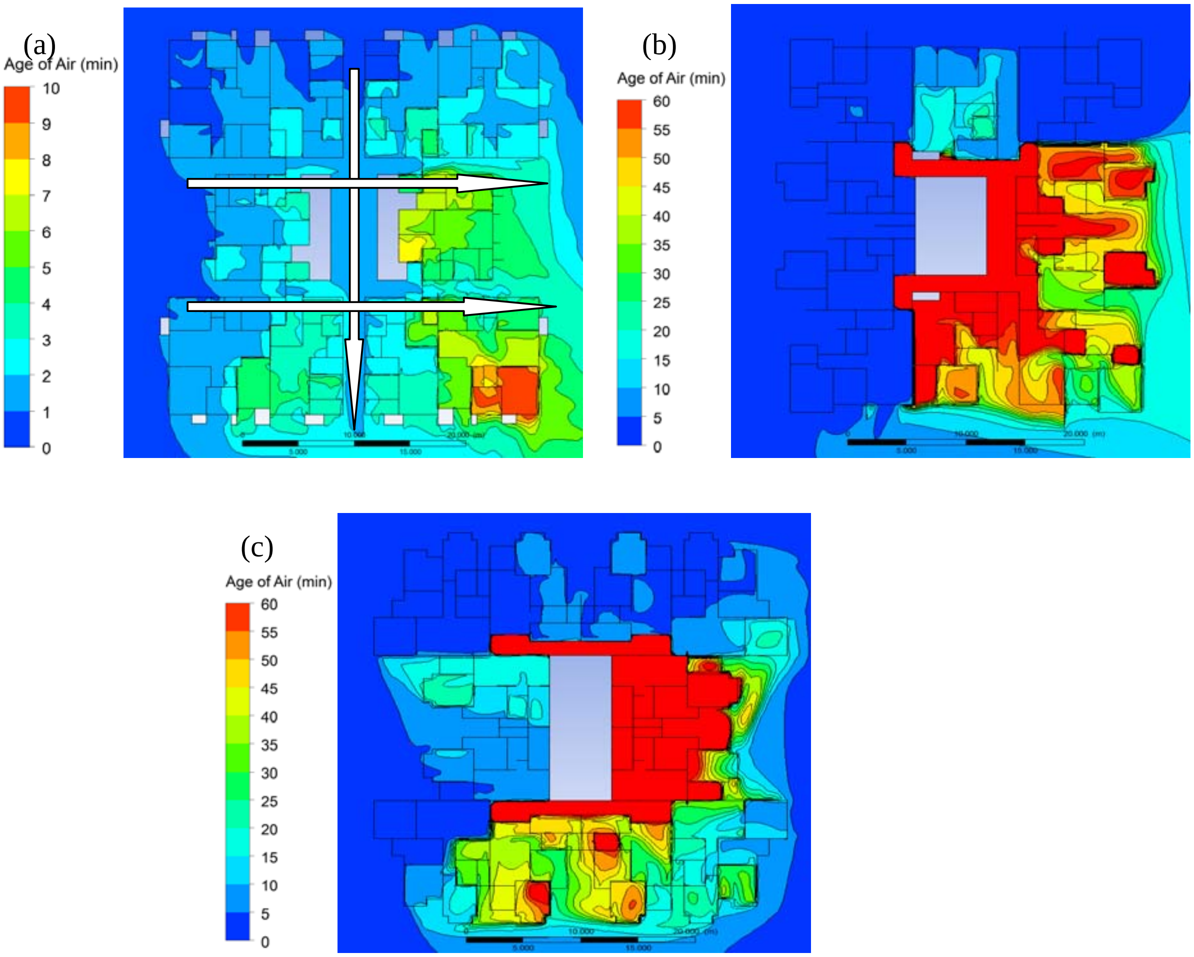

Fig. 6 Comparison of age of air with different floor plans: (a) optimized building; (b) Conventional Building 1; and (c) Conventional Building 2

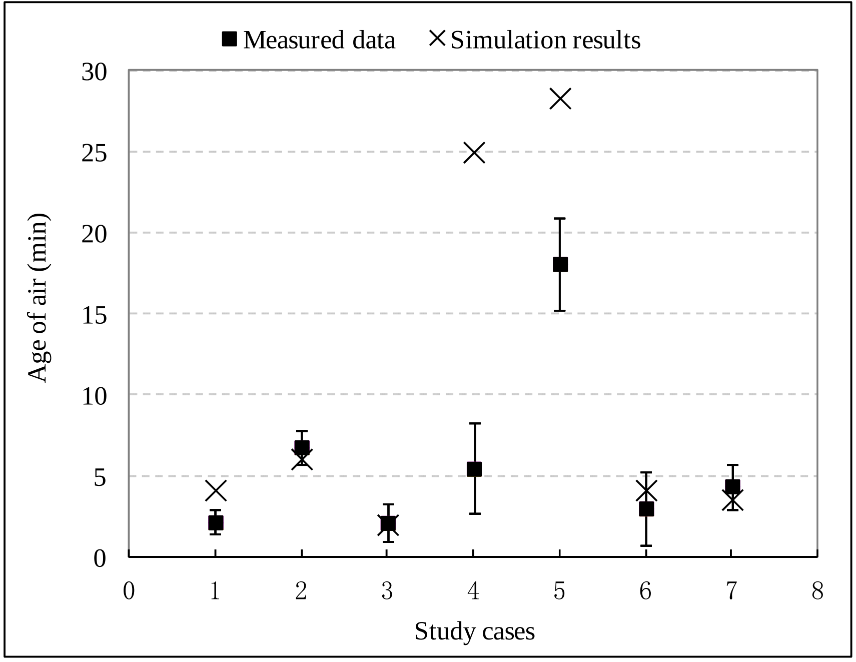

Fig. 7 Comparison of measured data with simulated results at Point 1

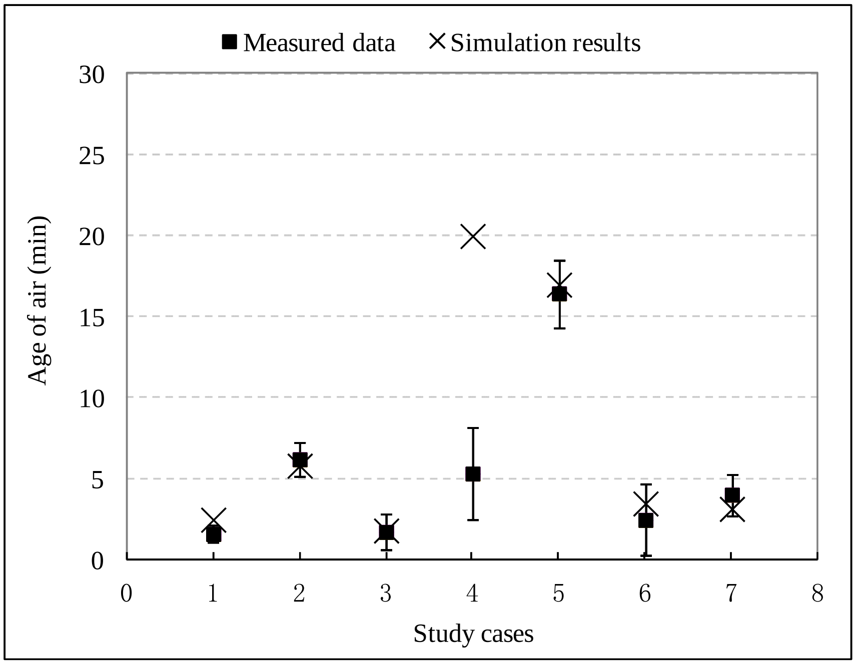

Fig. 8 Comparison of measured data with simulated results at Point 2