Determination of Optimal Air Change Rate for Cooling the Bedrooms of Residential Buildings in Guangzhou

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Abstract. Ventilation is a traditional strategy for cooling and energy saving in buildings in hot and humid climate. This study aims to develop correlations for calculating the optimal air change rate (ACH) for cooling that can be generally applied to residential buildings in Guangzhou. A bedroom prototype was built based on the typical design features of bedrooms, which were gotten through the investigation of 350 Guangzhou residential quarters. The impacts of three factors and ACH on cooling load were analyzed by simulations. ACH is the most important factor, followed by area ratio of window to wall, area and orientation. An increase from 5 to 10 ACH for 10-21 m² bedrooms could decrease annual cooling loads by an average of 17%, and prediction models of annual cooling loads were obtained for bedrooms by multiple regression, which were tested to be statistically valid. The predictive correlations of optimal ACH were finally achieved, which could be directly applied to the ventilation design of bedrooms in Guangzhou. The optimal ACH for prototype bedroom ranged from 21.99 to 22.85 h⁻¹ as change rate of ventilation contribution on cooling was 5%, and from 11.99 to 12.85 h⁻¹ as change rate of ventilation contribution on cooling was 10%.

1. Introduction
Ventilation is a traditional strategy for passive cooling in buildings in hot and humid climate. The contribution of ventilation to energy saving couldn’t be evaluated quantitatively until now in Chinese design standards, meanwhile the shading could be evaluated by the shading coefficient and the insulation of envelope by heat transfer coefficient and thermal inertia index. Natural ventilation has been widely studied and its performance on cooling and energy saving has been documented. Givoni [1] pointed that the indoor daytime air temperature would be reduced by night ventilation with the daily air temperature range of about 10º C. V. Geros et al. [2] examined that night ventilation techniques could decrease the next day peak indoor temperature by up to 3ºC. Tetsu Kubota et al. [3] argued that the cooling effect of night ventilation was larger than those of the other ventilation strategies during the day and night, and the night ventilation technique could lower the peak indoor air temperature by 2.5ºC and reduce nocturnal air temperature by 2.0ºC on average. Blondeau et al. [4] showed that the night ventilation would contribute to decreasing the diurnal indoor air temperature by 2 ºC, as the averaged daily air temperature range was 8.4ºC. M. Santamouris [5] found that energy contribution of night ventilation in residential buildings may decrease the cooling energy consumption up to 40 kWh/m²/y for various levels of air flow rate and in particular for 2, 5, 10, 20 and 30 h⁻¹.
Natural ventilation can be achieved by opening windows or doors, and its performance depends on outdoor climate as well as plan and construction of buildings. Therefore, cooling effect of natural ventilation is always varied and out of controlled, and cooling potential of outdoor climate may not be fully utilized through natural ventilation. Taking into account of those shortages, mechanical ventilation is considered to be a good supplement to natural ventilation. Numerous studies have been previously conducted on mechanical ventilation of buildings, which were mainly focused on ACH, energy saving, design and control strategies for indoor thermal comfort, contaminants, and health requirements. For example, Katerina Niachou [6] estimated the indoor exchange rates of natural, mechanical and hybrid ventilations through the tracer gases measurements. The mean ACH in a unit equipped with a transom ventilation panel is 27% greater than a unit without it [7]. For state-of-the-art buildings ventilation energy losses in the heating season are easily compensated by lower cooling demand in the warm period of the year [8]. Pavlovas [9] studied a demand controlled ventilation system by controlling carbon dioxide concentration for a typical Swedish multifamily building with exhaust ventilation. David Jreijiry [10] studied a mechanical extract ventilation system and a hybrid low pressure ventilation system that could support two different types of demand control strategies (occupancy detection and CO$_2$ concentration) in residential buildings. Moreover, a dynamic control strategy for residential mechanical ventilation can provide the indoor air quality benefits intended by the ASHRAE standard at substantially reduced energy costs (typically between 20% and 40%) [11].

Guangzhou, located in south of China, has subtropical climatic background with a long and hot-humid summer. Figure 1 shows annual average monthly temperature and relative humidity based on typical meteorological year data of Guangzhou [12], which was obtained based on the nearly 30 years’ measured meteorological data issued by the China Meteorological Administration. It can be seen from the figure 1 that the monthly average air temperature is higher than 24°C from May to October and the monthly average relative humidity is between 60.9% and 84.1%. With the long and hot-humid summer, energy consumed by residential buildings accounted for 19% of the total energy consumption in Guangzhou in 2010 [13], and an apparent increasing tendency of energy consumption has been observed in residential buildings of Guangzhou during the last few decades. The annual electricity consumption by households has dramatically increased from 42.98 kWh/m$^2$ in 1990 to 104.65 kWh/m$^2$ in 2010 [13]. Ventilation is an excellent strategy to slow down such a tendency, because the cooling effects of ventilation can greatly decrease energy consumption of household air conditionings, which contributes to the largest part of electricity consumption of residential buildings.

Determination of optimal ACH for cooling is the key of well ventilation design and energy conservation of residential buildings in Guangzhou. However, very few studies have reported such optimal ACH considering its cooling and energy saving effects. Cuicui Qin [14] reported that contribution of ventilation on energy saving became more significant while ACH reached 20 h$^{-1}$. Weiwei Du [15] showed that the reasonable ACH was 12 h$^{-1}$ for bedrooms in Guangzhou. The above results were achieved based on specific cases. Many factors, such as orientation, area ratio of window to wall, building envelope constructions and climate conditions, have the influence on energy consumption of building, and then the optimal ACH for cooling will be very different for various cases. The existed information on ACH is lack of general applicability for residential buildings in Guangzhou.

Consequently, the present study aimed to determinate the optimal ACH for cooling that can be generally applied to residential buildings in Guangzhou. Bedrooms that are most often occupied and consuming large part of cooling energy are mainly focused. The basic design features of bedrooms were investigated through 350 Guangzhou residential quarters, based on which a prototype was built. The constructions of envelopes were set according to the current standards, and the dynamic thermal simulation program DeST was applied to simulate the annual cooling loads of the prototype. The impacts of ACH and three factors, i.e., area, orientation and area ratio of window to wall on cooling load were analyzed by orthogonal experiment design. Finally, prediction correlations of optimal ACH were obtained, which could be directly applied to the ventilation design of bedrooms in Guangzhou.
2. Basic Design Features of Bedrooms in Guangzhou

A survey was carried out to achieve the basic design features of bedrooms in Guangzhou. The features that were considered to possibly affect the determination of optimal ACH were investigated, including orientation, area, length, width and area ratio of window to wall. Totally 350 residential quarters of Guangzhou built in recent years were collected and analyzed, as shown in figures 1-4.

![Figure 1. Annual average monthly temperature and relative humidity in typical meteorological data year of Guangzhou.](image1)

![Figure 2. Frequency distribution of area for bedrooms in Guangzhou.](image2)

![Figure 3. Frequency distribution of ratio of length to width for bedrooms in Guangzhou.](image3)

![Figure 4. Frequency distribution of area ratio of window to wall for bedrooms in Guangzhou.](image4)

![Figure 5. Frequency distribution of orientation for bedrooms in Guangzhou.](image5)

The frequency distribution of area for bedrooms in Guangzhou was shown in figure 2. The frequently encountered areas were 12-13 m² (14%), 11-12 m² (10%) and 8-9 m² (9.8%). The frequency of the bedrooms with greater than 21 m² or below 7 m² was only 4% and 1.9%, respectively. So the main area of bedrooms in Guangzhou could be considered as 7-21 m².
The geometry of bedroom was determined not only by its area, but also by the ratio of length to width. The frequency of ratio of length to width for bedrooms in Guangzhou was shown in figure 3. The most common ratio of length to width was 1.1-1.2 (21%), and then 1.2-1.3 (7%), so the typical ratio of length to width for bedrooms in Guangzhou was considered as 1.1-1.3.

The frequency distribution of area ratio of window to wall for bedrooms in Guangzhou was shown in figure 4. The most encountered area ratio of window to wall was 0.30-0.35 (27%), 0.35-0.40 (17%) and 0.25-0.30 (14%). So the typical area ratio of window to wall for bedrooms in Guangzhou was then obtained as 0.30-0.50.

The frequency distribution of bedroom orientation in Guangzhou was shown in figure 5. South and north orientations occupied most of the cases (69%), mainly because that these orientation can avoid solar radiation in summer. The bedrooms towards west and east accounted for 11% and 8% of the cases respectively, and the bedrooms towards southeast, northeast, southwest and northwest had only limited proportion less than 5%.

3. Determination of Optimal ACH for Cooling

3.1. Method

3.1.1. The Simulation Software DeST

- General information
  Designer’s Simulation Toolkits (DeST) was started by Tsinghua University for the aims of benefit for practical and research use of building simulation related applications in China in early 1980s [16]. DeST was designed to apply state space method [17] to dynamically simulate building thermal progress and predict hourly temperatures inside buildings and annual heating or cooling loads for the whole building or various zones [18].

- Validation and applicability
  The source program of DeST was tested together with other 25 well known programs by International Energy Agency (IEA) Annex 21 with the method of internal model comparison and empirical comparison [19]. In some national and local energy efficiency regulations, DeST has been regarded as a prediction and evaluation tool to judge that a building meets the requirements of codes or not [20], and it was considered to be one of the best thermal simulation programs in the world [21, 22].

- State-of-the-art simulation strategy
  The variable ventilation model [23] provided by DeST was applied to study cooling effect of ventilation. Tolerance temperature was first to be set for each occupied zones. When indoor air temperature is lower than tolerance temperature, no ventilation or mechanical cooling is needed. When indoor air temperature is higher than tolerance temperature, ventilation is used for cooling only if the ventilation can lower indoor air temperature below tolerance temperature, otherwise air conditioning is provided.

3.1.2. A Prototype for Simulation.

A prototype for simulation was established based on the survey of design features for bedrooms in Guangzhou. It was combined by 5 floors and the height for each floor was 3 m. The layout of each floor was shown in figure 6, from which it can be seen that there are 6 bedrooms, and they can be divided into two types: type 1 with one side of exterior wall and type 2 with two sides of exterior walls. The No.1 and No.2 bedrooms are different on orientation of their headwall. The length to width of each bedroom is designed in range of 1.1-1.3.
The envelopes of the prototype were set according to the requirement of current energy efficiency standard for Guangzhou [24]. The main structure of the prototype was reinforced concrete with aerated concrete walls in thickness of 200 mm, and average heat transfer coefficient of the exterior walls was 1.5 W/(m²·K). Reinforced concrete board in thickness of 100mm with 30mm polystyrene were used on the roof, and its average heat transfer coefficient was 1.0 W/(m²·K). Windows were metal frame and single glazing of 6 mm clear glass. The heat transfer coefficient and the shading coefficient of the windows was 6.5 W/(m²·K) and 0.80, respectively. The above settings of envelopes were widely used for the residential buildings in Guangzhou, which were considered to save 50% of energy consumption of the prototype compared to the general structures in 1980s.

Air conditioner was usually operated from March 15th to October 15th [14], and the detail operating time was shown in the table 1. The indoor set-point and tolerance temperature were selected as 24 °C and 29 °C, respectively. The heat and moisture gains from occupants were regarded to be 57 W/p and 68 g/h/p respectively when they were in bedroom [25]. Internal heat gain from lighting was 7 W/m² [26], and detail schedule of lighting and person occupy were shown in table 1.

Table 1. Schedule of different loads.

| Indoor environment          | Mon-Fri          | Sat-Sun         |
|-----------------------------|------------------|-----------------|
|                             | Time             | Time            |
|                             | Fraction         | Fraction        |
| Air conditioning and        | 22:00-07:00      | 23:00-09:00     |
| ventilation                 | —                | —               |
|                             | 07:00-18:00      | 09:00-13:00     |
|                             | 0.0              | 0.0             |
|                             | 18:00-22:00      | 13:00-14:00     |
|                             | 0.5              | 1.0             |
| Person                      | 22:00-07:00      | 14:00-19:00     |
|                             | 1.0              | 0.0             |
|                             | 19:00-22:00      | 19:00-22:00     |
|                             | 0.5              | 0.5             |
|                             | 22:00-09:00      | 22:00-09:00     |
|                             | 1.0              | 1.0             |
| Lighting                    | 18:00-22:00      | 19:00-22:00     |
|                             | 0.5              | 0.5             |
|                             | 22:00-23:00      | 22:00-24:00     |
|                             | 1.0              | 1.0             |
The meteorological data of typical year in Guangzhou was used as outdoor climate data, including outdoor dry-bulb air temperature, relative humidity, solar direct radiation, solar diffuse radiation, sky long-wave radiation temperature, wind speed and wind direction. The data was obtained based on the nearly 30 years’ measured meteorological data [12] and issued by the China Meteorological Administration.

3.1.3. Orthogonal Design of Simulation Cases. Four key design features of bedroom, i.e., orientation, area, ratio of length to width and area ratio of window to wall, were considered to potentially affect the optimal ACH. Orthogonal experiment design (hereafter referred as OED) [27, 28] was applied to determine the simulation cases as a good design methodology for multi-factors and multi-levels. Many standard orthogonal arrays can be tabulated by Statistical Product and Service Solutions (SPSS) [29, 30] for using orthogonal method. SPSS is a modular data management and analysis application created and produced by SPSS, Inc., in Chicago, Illinois [31]. And its features are modules for statistical data analysis, including descriptive statistics such as plots, frequencies, charts, and lists, as well as sophisticated inferential and multivariate statistical procedures like analysis of variance (ANOVA), factor analysis, cluster analysis, and categorical data analysis [32].

Influencing factors and their values of the OED were shown in table 2. According to the residential building design standard of China [33], the area of bedrooms for two persons should be not less than 10 m$^2$, so the typical bedroom area was decided as 10-21 m$^2$ in the simulation. Five levels of area were then obtained considering the typical ratio of length to width in range of 1.1-1.3. Eight bedroom orientations were considered. The conditions of area ratio of window to wall were evenly divided into five levels in the typical range of 0.30-0.50, and eight ACH levels in the range of 5-40 h$^{-1}$ were selected. So the experimental region spanned the four factors. Notably, five levels were selected for the factors of area and area ratio of window to wall, and the other two factors of ACH and orientation had eight levels. A total of four factors and their levels, standard orthogonal arrays can be tabulated by SPSS for using orthogonal method. The appropriate mixed level orthogonal design form $L_{64}(5^2 \times 8^2)$, selected from the design module of SPSS, was used, which has 8-level columns at most and 64 rows corresponding to 64 simulation cases, as shown in table 3. The blank column was omitted and repetitive tests for each case were carried out to reduce the error of results.

Table 2. Influencing factors and their values in orthogonal experimental design.

| No. | Factors                     | Levels | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       |
|-----|-----------------------------|--------|---------|---------|---------|---------|---------|---------|---------|---------|
| 1   | Area, m$^2$                 |        | 10.80   | 12.87   | 15.12   | 17.55   | 20.16   |         |         |         |
| 2   | Orientation                 |        | 0(E)    | $\pi/4$ | $\pi/2$ | $3\pi/4$ | $\pi/4$ | 5$\pi/4$ | 3$\pi/2$ | 7$\pi/4$ |
| 3   | Area ratio of window to wall|        | 0.30    | 0.35    | 0.40    | 0.45    | 0.50    |         |         |         |
| 4   | Air change rate, h$^{-1}$   |        | 5       | 10      | 15      | 20      | 25      | 30      | 35      | 40      |

E: East  
NE: Northeast  
N: North  
NW: Northwest  
W: West  
SW: Southwest  
S: South  
SE: Southeast

Table 3. Setting of numerical simulation cases by table of orthogonal arrays of L64 ($5^2 \times 8^2$).

| No. | 1 | 2 | 3 | 4 | Area (m$^2$) | Orientation | Area ratio of Window to wall | Air change rate (h$^{-1}$) |
|-----|---|---|---|---|-------------|-------------|-----------------------------|---------------------------|

The appropriate mixed level orthogonal design form $L_{64}(5^2 \times 8^2)$, selected from the design module of SPSS, was used, which has 8-level columns at most and 64 rows corresponding to 64 simulation cases, as shown in table 3. The blank column was omitted and repetitive tests for each case were carried out to reduce the error of results.
| No. | 1   | 2   | 3   | 4   | Area (m²) | Orientation | Area ratio of Window to wall | Air change rate (h⁻¹) |
|-----|-----|-----|-----|-----|-----------|-------------|--------------------------|----------------------|
| 1   | 1   | 1   | 1   | 1   | 10.80     | East        | 0.30                     | 5                    |
| 2   | 1   | 1   | 6   | 1   | 10.80     | Southwest   | 0.30                     | 20                   |
| 3   | 1   | 1   | 1   | 6   | 10.80     | East        | 0.30                     | 30                   |
| 4   | 1   | 6   | 1   | 7   | 10.80     | Southwest   | 0.30                     | 35                   |
| 5   | 1   | 5   | 2   | 3   | 10.80     | West        | 0.35                     | 15                   |
| 6   | 1   | 7   | 2   | 3   | 10.80     | South       | 0.35                     | 15                   |
| 7   | 1   | 4   | 2   | 5   | 10.80     | Northwest   | 0.35                     | 25                   |
| 8   | 1   | 2   | 2   | 5   | 10.80     | Northwest   | 0.35                     | 25                   |
| 9   | 1   | 3   | 3   | 1   | 10.80     | North       | 0.40                     | 5                    |
| 10  | 1   | 8   | 3   | 4   | 10.80     | Southeast   | 0.40                     | 20                   |
| 11  | 1   | 3   | 3   | 6   | 10.80     | North       | 0.40                     | 30                   |
| 12  | 1   | 8   | 3   | 7   | 10.80     | Southeast   | 0.40                     | 35                   |
| 13  | 1   | 4   | 4   | 2   | 10.80     | Northwest   | 0.45                     | 10                   |
| 14  | 1   | 7   | 4   | 8   | 10.80     | South       | 0.45                     | 40                   |
| 15  | 1   | 2   | 5   | 2   | 10.80     | Northeast   | 0.50                     | 10                   |
| 16  | 1   | 5   | 5   | 8   | 10.80     | West        | 0.50                     | 40                   |
| 17  | 2   | 2   | 7   | 1   | 5.87      | South       | 0.30                     | 25                   |
| 18  | 2   | 2   | 1   | 6   | 12.87     | Northeast   | 0.30                     | 30                   |
| 19  | 2   | 5   | 1   | 7   | 12.87     | West        | 0.30                     | 35                   |
| 20  | 2   | 4   | 1   | 8   | 12.87     | Northwest   | 0.30                     | 40                   |
| 21  | 2   | 8   | 2   | 1   | 12.87     | Southeast   | 0.35                     | 5                    |
| 22  | 2   | 1   | 2   | 2   | 12.87     | East        | 0.35                     | 10                   |
| 23  | 2   | 1   | 2   | 7   | 12.87     | East        | 0.35                     | 35                   |
| 24  | 2   | 8   | 2   | 8   | 12.87     | Southeast   | 0.35                     | 40                   |
| 25  | 2   | 4   | 3   | 1   | 12.87     | Northeast   | 0.40                     | 5                    |
| 26  | 2   | 5   | 3   | 2   | 12.87     | West        | 0.40                     | 10                   |
| 27  | 2   | 2   | 3   | 3   | 12.87     | Northeast   | 0.40                     | 15                   |
| 28  | 2   | 7   | 3   | 4   | 12.87     | South       | 0.40                     | 20                   |
| 29  | 2   | 3   | 4   | 5   | 12.87     | North       | 0.45                     | 25                   |
| 30  | 2   | 6   | 4   | 6   | 12.87     | Southwest   | 0.45                     | 30                   |
| 31  | 2   | 6   | 5   | 3   | 12.87     | Southwest   | 0.50                     | 15                   |
| 32  | 2   | 3   | 5   | 4   | 12.87     | North       | 0.50                     | 20                   |
| 33  | 3   | 8   | 1   | 2   | 15.12     | Southeast   | 0.30                     | 10                   |
| 34  | 3   | 3   | 1   | 3   | 15.12     | North       | 0.30                     | 15                   |
| 35  | 3   | 8   | 1   | 5   | 15.12     | Southeast   | 0.30                     | 25                   |
| 36  | 3   | 3   | 1   | 8   | 15.12     | North       | 0.30                     | 40                   |
| 37  | 3   | 4   | 2   | 4   | 15.12     | Northwest   | 0.35                     | 20                   |
| 38  | 3   | 2   | 2   | 4   | 15.12     | Northeast   | 0.35                     | 20                   |
| 39  | 3   | 7   | 2   | 6   | 15.12     | South       | 0.35                     | 30                   |
| 40  | 3   | 5   | 2   | 6   | 15.12     | West        | 0.35                     | 30                   |
| 41  | 3   | 6   | 3   | 2   | 15.12     | Southwest   | 0.40                     | 10                   |
| 42  | 3   | 1   | 3   | 3   | 15.12     | East        | 0.40                     | 15                   |
| 43  | 3   | 6   | 3   | 5   | 15.12     | Southwest   | 0.40                     | 25                   |
| 44  | 3   | 1   | 3   | 8   | 15.12     | East        | 0.40                     | 40                   |
| 45  | 3   | 5   | 4   | 1   | 15.12     | West        | 0.45                     | 5                    |
| 46  | 3   | 2   | 4   | 7   | 15.12     | Northeast   | 0.45                     | 35                   |
| 47  | 3   | 7   | 5   | 1   | 15.12     | South       | 0.50                     | 5                    |
| 48  | 3   | 4   | 5   | 7   | 15.12     | Northwest   | 0.50                     | 35                   |
| No. | 1 | 2 | 3 | 4 | Area (m²) | Orientation | Area ratio of Window to wall | Air change rate (h⁻¹) |
|-----|---|---|---|---|-----------|-------------|--------------------------|----------------------|
| 49  | 4 | 7 | 1 | 2 | 17.94     | South       | 0.30                      | 10                   |
| 50  | 4 | 4 | 1 | 3 | 17.94     | North       | 0.30                      | 15                   |
| 51  | 4 | 6 | 2 | 1 | 17.94     | Northwest   | 0.35                      | 5                    |
| 52  | 4 | 3 | 2 | 7 | 17.94     | North       | 0.35                      | 35                   |
| 53  | 4 | 5 | 3 | 5 | 17.94     | West        | 0.40                      | 25                   |
| 54  | 4 | 2 | 3 | 8 | 17.94     | Northeast   | 0.40                      | 40                   |
| 55  | 4 | 1 | 4 | 4 | 17.94     | East        | 0.45                      | 20                   |
| 56  | 4 | 8 | 5 | 6 | 17.94     | Southeast   | 0.50                      | 30                   |
| 57  | 5 | 6 | 2 | 8 | 20.16     | Northeast   | 0.30                      | 5                    |
| 58  | 5 | 4 | 3 | 6 | 20.16     | West        | 0.30                      | 20                   |
| 59  | 5 | 7 | 3 | 7 | 20.16     | North       | 0.35                      | 10                   |
| 60  | 5 | 8 | 4 | 3 | 20.16     | Southwest   | 0.35                      | 40                   |
| 61  | 5 | 1 | 5 | 5 | 20.16     | Northwest   | 0.40                      | 30                   |
| 62  | 5 | 2 | 1 | 1 | 20.16     | South       | 0.40                      | 35                   |
| 63  | 5 | 5 | 1 | 4 | 20.16     | Southeast   | 0.45                      | 15                   |
| 64  | 5 | 3 | 2 | 2 | 20.16     | East        | 0.50                      | 25                   |

4. Results and Discussions

4.1. Annual Cooling Loads

Each simulation case was shown in table 3. Results of bedrooms in the middle floor were analyzed, which could represent the most general situations and avoid the influence of the roof or ground. For the bedrooms with two sides of exterior walls, the No.1 and No.2 bedrooms have one headwall with opposite orientations. The annual cooling loads and relative deviation of No.1 and No.2 bedrooms for each case was shown in figure 7. The annual cooling loads of No.1 bedroom were much closer to that of No.2 bedroom, and relative deviation between No.1 and No.2 bedrooms in each case was less than 3%. Therefore, annual cooling loads of bedroom with two sides of exterior walls were considered to be the average value of No.1 and No.2 bedrooms.

![Figure 7. The annual cooling loads of No.1 and No.2 bedrooms with two sides of exterior walls obtained by the DeST software and the relative deviation between them.](image)

The influence trends of parameters on the annual cooling loads obtained from each case were analyzed by the intuitive analysis method. The average annual cooling loads for each level of each factor were calculated. For example, for the level 1 of the area (table 2), the average value was considered as the average of annual cooling loads of all the level 1 rows in area (table 3). In such a way,
the average values for other factors and levels were obtained and the impacts of various factors on annual cooling loads were shown in figure 8.

![Figure 8. The impacts of various factors on annual cooling loads.](image)

It can be seen from figure 8 that the annual cooling loads of both types of bedrooms changed in a similar tendency, and the cooling loads of bedrooms with two sides of exterior walls were slightly higher than that with one side of exterior wall. Area had a negative effect on cooling load that annual cooling loads per square meter decrease linearly with increasing area of bedroom. In contrast to the effects of area, area ratio of window to wall has a positive effect on cooling load due to the increased internal heat gains from solar radiation.

Figure 8 also showed that cooling load changed with orientation. The orientations of west and east made the cooling load larger and south and north made it smaller. Compared to above three factors, ACH has much more significant impact on annual cooling loads. An increase of ACH from 5 to 10 could produce an average decrease of annual cooling loads 8 kW/m$^2$ corresponding to energy saving 17%, and the impact of ventilation on cooling loads decreased while ACH was increasing.

### 4.2. Prediction Model of Annual Cooling Loads

Taking annual cooling loads of bedroom as dependent variable and four factors, i.e., orientation, area, area ratio of window to wall and ACH, as independent variables, a prediction model of annual cooling loads was obtained by multiple linear regression method [26]. The model for bedrooms with one side of exterior wall was given as follows:

$$ Y = -1.337X_1 + 65.232X_2 - 0.632X_3 - 0.588X_4 + 35.92 $$

The model for bedrooms with two sides of exterior walls was obtained as:

$$ Y = -1.311X_1 + 58.139X_2 - 0.593X_3 - 0.465X_4 + 37.692 $$

where $Y$ (kWh/m$^2$) is annual cooling loads of bedrooms, $X_1$ (m$^2$) is area, $X_2$ is area ratio of window to wall, $X_3$ (h$^{-1}$) is ACH and $X_4$ is orientation.

The regression models were validated by correlation coefficient, collinearities and $t$-test and $F$-test by a significance level of 0.05. For the validation of the regression models, adjusted ($R^2$) of predicted results for each model was calculated (with a significance level of 0.05) and compared with the coefficient of determination ($R^2$). Regression model is valid if coefficient of determination ($R^2$) is higher than the adjusted ($R^2$). Table 4 showed the correlation coefficient and variance analysis of regression models. It was noted from the table that Correlation (1) and Correlation (2) had a great
adjusted ($R^2$) of 77.5% and 80.5%, respectively, below the coefficient of determination ($R^2$), and $F$-test (Sig. >0.05) was valid, thus annual cooling loads of bedrooms can be predicted by orientation, area, area ratio of window to wall and ACH.

### Table 4. Statistical information and variance analysis of regression models.

| Model | $R^2$ (%) | Adjusted $R^2$ (%) | Std. Error of the Estimate | $F$   | Sig.    |
|-------|-----------|---------------------|---------------------------|-------|---------|
| 1     | 78.9      | 77.5                | 5.084                     | 55.310| 0.000   |
| 2     | 81.7      | 80.5                | 4.354                     | 65.917| 0.000   |

### Table 5. Regression coefficient, tests of significance and collinearity.

| Model | Unstandardized coefficients | Standardized coefficients | t    | Sig.    | Collinearity statistics |
|-------|-----------------------------|---------------------------|------|---------|-------------------------|
|       | B                           | Std. Error                |      |         | Tolerance   | VIF    |
| 1     | (Constant)                  | 35.920                    | 5.018| 7.159   | 0.000       | 1.000  | 1.000  |
|       | Bedroom area                | -1.337                    | 0.204| -0.391  | -6.540      | 0.000  | 1.000  | 1.000  |
|       | Orientation                 | -0.588                    | 0.353| -0.099  | -1.663      | 0.102  | 1.000  | 1.000  |
|       | Window to wall area ratio   | 65.232                    | 9.651| 0.404   | 6.759       | 0.000  | 1.000  | 1.000  |
|       | Air change rate             | -0.632                    | 0.055| -0.681  | -11.402     | 0.000  | 1.000  | 1.000  |
| 2     | (Constant)                  | 37.692                    | 4.298| 8.771   | 0.000       | 1.000  | 1.000  |
|       | Bedroom area                | -1.311                    | 0.175| -0.417  | -7.491      | 0.000  | 1.000  | 1.000  |
|       | Orientation                 | -0.465                    | 0.303| -0.086  | -1.537      | 0.130  | 1.000  | 1.000  |
|       | Window to wall area ratio   | 58.139                    | 8.266| 0.392   | 7.034       | 0.000  | 1.000  | 1.000  |
|       | Air change rate             | -0.593                    | 0.048| -0.695  | -12.479     | 0.000  | 1.000  | 1.000  |

Table 5 showed the regression coefficients, t-test and multiple collinearity statistics of the variables, and these coefficients provided a measure of the linear relationship between the independent and dependent variables. It can be seen from table 5 that each variable in both regression models showed a great significance with a sig. value of t-test below 0.5, except orientation. After that, the standardized regression coefficients of the variables shown in table 5 demonstrated that the impacts of the factors on the annual cooling loads of bedroom were different and in descending order of ACH, area ratio of window to wall, bedroom area and the orientation. It also showed that there were no collinearities during the variables with the valid inflation factor below 2.0. Based on above tests and analysis, the predicted correlations (1) and (2) are considered to be statistically valid and reliable, which can be applied to the calculation of annual cooling loads of bedroom in Guangzhou.

### 4.3. Determination of Optimal Air Change Rate

Contribution of ventilation on cooling was used to quantitatively evaluate cooling and energy saving effect of ventilation, which is defined as the reduction rate of annual cooling loads due to the enhanced ventilation and expressed as:

$$R = \frac{Y_{base} - Y_n}{Y_{base}} \times 100\%$$

(3)

where $R$ (%) represents contribution of ventilation on cooling, $n$ (h$^{-1}$) is ACH, $Y_n$ (kWh/m$^2$) is annual cooling loads of bedroom with $n$ ACH, $Y_{base}$ (kWh/m$^2$) is annual cooling loads of bedroom with normal ventilation, i.e., ACH of 30m$^3$/h/person required by indoor air quality standard in China [34].
It can be seen from Figure 8 that contribution of ventilation on cooling is increasing apparently with the increase of ACH from 5 to 20 h\(^{-1}\), while the tendency is slowed down as ACH is higher. Considering higher ACH needs larger cost and makes more negative impacts like noise and installation space, a balance should be made between utilizing cooling potential and controlling cost and negative impacts. So, change rate of contribution was achieved by the following Correlation:

\[
CR = \frac{R_n - R_{n-1}}{R_{n-1}} = \frac{Y_n - Y_{n-1}}{Y_{n-1} \cdot Y_{\text{base}}} \times 100\%
\]  

(4)

where \(CR\) (%) is change rate of contribution, \(R_n\) (%) is contribution rate of ventilation on cooling with \(n\) ACH, \(R_{n-1}\) (%) is contribution rate of ventilation on cooling with \(n-1\) ACH.

Then based on the prediction models of annual cooling loads (Correlation (1) or (2)) and contribution of ventilation on cooling (Correlation (3)) into Correlation (4), the Correlation (5) can be achieved as follows:

\[
n = \frac{1}{CR} + 1 + n_{\text{base}} = \frac{1}{CR} + 1 + \frac{60}{H \times A}
\]  

(5)

where \(n_{\text{base}}\) (h\(^{-1}\)) is ACH corresponding 30 m\(^3\)/h/p, \(H\) (m) is height of bedroom, \(A\) (m\(^2\)) is area of bedroom.

If we set a low limit for \(CR\) according to practical considerations on ventilation cost or negative impacts, then an optimal ACH for cooling can be obtained by Correlation (5). For example, if height of the bedroom is 3 m and low limit of \(CR\) is set to be 10%, then the optimal ACH can be expressed as:

\[
n = 11 + \frac{20}{A}
\]  

(6)

and for low limit of \(CR\) 5%, it can be expressed as:

\[
n = 21 + \frac{20}{A}
\]  

(7)

The prediction correlation of optimal ACH for cooling, i.e., correlation (5), can be directly and conveniently applied to the ventilation design of bedrooms in Guangzhou. Figure 9 shows the optimal ACH for typical bedrooms with area range from 10 to 21 m\(^2\) in two levels of \(CR\). It is obvious that optimal ACH has a declining tendency with increasing area of bedroom. The optimal ACH for bedrooms with area of 10.80 m\(^2\), 12.87 m\(^2\), 15.12 m\(^2\), 17.94 m\(^2\) and 20.16 m\(^2\) is 12.85 h\(^{-1}\), 12.55 h\(^{-1}\), 12.32 h\(^{-1}\), 12.11 h\(^{-1}\) and 11.99 h\(^{-1}\) respectively for \(CR\) of 10\%, and it is 22.85 h\(^{-1}\), 22.55 h\(^{-1}\), 22.32 h\(^{-1}\), 22.11 h\(^{-1}\) and 21.99 h\(^{-1}\) respectively for \(CR\) of 5\%.

Figure 9. The optimal ACH for the typical area of bedroom.

5. Conclusions
The optimal ACH for cooling and energy saving was determined in the present paper for bedrooms of
residential buildings in Guangzhou, and the main conclusions were as follows.

The prototype bedrooms in Guangzhou had the following design features: area is in the range of 7-21 m$^2$, ratio of length to width is between 1.1 and 1.3, area ratio of window to wall is in range of 0.30-0.50 and orientation is south and north.

Considering three basic design factors, i.e., area, orientation and area ratio of window to wall with ACH together, prediction models of annual cooling loads were obtained for bedrooms in Guangzhou, which were tested to be statistically valid and reliable.

The impacts of area ratio of window to wall, area, orientation of bedroom and ACH on cooling load were analyzed by orthogonal method and thermal simulations, and they were in descending order of ACH, area ratio of window to wall, area and orientation.

An increase of ACH from 5 to 10 h$^{-1}$ for the bedroom area 10-21 m$^2$ could produce an average decrease of annual cooling loads 8 kW/m$^2$ corresponding to saving 17% energy, and the impact of ventilation on cooling load decreased with increasing ACH.

The predictive correlations of optimal ACH for cooling were achieved, which could be directly and conveniently applied to the ventilation design of bedrooms in Guangzhou. The optimal ACH for typical bedrooms ranged from 21.99 to 22.85 h$^{-1}$ as low limit of change rate of ventilation contribution on cooling was set as 5%, and from 11.99 to 12.85 h$^{-1}$ as was low limit of 10%.

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