Numerical simulation and site measurements of ventilation efficiency for different types of air-conditioned rooms through window-opening natural ventilation

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Abstract. To study the air exchange efficiency of rooms while air conditioning equipment are running and window is open, this paper used the experiments of tracer gas CO\textsubscript{2} to measure its concentration variations indoor after opening window. At the same time, the corresponding cases were simulated numerically with computational fluid dynamic (CFD). The experimental results showed that after opening window, the combined action of wind pressure and pressure due to the differences of the air density can cause obvious air exchange between the indoor and the outdoor. Indoor CO\textsubscript{2} concentration was continuously reduced as proceeding of the air infiltration and there is an optimized width of window opening which resulted in a fastest decay rate of CO\textsubscript{2} concentration. Furthermore, results of simulation and experiment indicated that larger temperature difference between the indoor and outdoor lead to faster indoor CO\textsubscript{2} exhausted rates. Air exchange rate of air-conditioned rooms is affected by the types, opening degrees and the relative locations of the window as well. Natural ventilation by reasonable window opening can enhance the air quality if the outside air is not polluted. It should be noticed that optimized width and relative location of the window opening exist if economy is to be considered.

1. Introduction
People spend most of their time in buildings, but many buildings are air-conditioned without mechanical fresh air supply system equipped. Through the questionnaire survey, in order to obtain fresh air and discharge the polluted indoor air after repeated filtration, many people chose opening window for ventilating while air conditioning equipment are running so as to improve the indoor air quality. Therefore, it is important to study the air exchange efficiency of these rooms in order to judge the indoor air quality, ventilation efficiency and promote the indoor environment. The tracer-gas method is commonly used to measure the ventilation rates in natural ventilation buildings [1]. As a tracer gas with a large ventilation volume in the test room, CO\textsubscript{2} has been used by many scholars. Some studies have shown that CO\textsubscript{2} as a release source has certain reliability in measuring ventilation frequency in the dormitory [2].
In the case of natural ventilation, Nowa et al. [3] analyzed the ventilation rate and indoor air quality in the office by using the CO2 tracer gas concentration attenuation method. Also using CO2 as a tracer gas, Lijin B. [4] used two methods, the attenuation method and the stabilization method, to calculate the room air exchange rate. Xiaofeng L. [5] discussed the effect of different indoor layouts and the opening of doors and windows on the measurement of air replacement rate. In the case of mechanical ventilation, some scholars also use the CO2 tracer gas concentration attenuation method to determine the air change rate [6]. In addition, Xianting Li. et al. [7] used methane as a tracer gas to measure the air age at various indoor measurement points. There are also scholars comparing the measurement accuracy of two tracer gases, CO2 and SF6, under the conditions of natural mixed ventilation and mechanical mixed ventilation [8]. It can be found that most studies only use experimental measurement methods to illustrate the ventilation efficiency, however, computational fluid dynamics (CFD) is also a cheap and reliable method to study the indoor air condition [11]. In this paper, CO2 is used as a tracer gas, and the effects of natural ventilation of windows in different types of air-conditioned rooms on indoor air quality are studied both through experiments with indoor tracer gases and CFD numerical simulation.

2. Site measurements
A 3.86 m long, 3.06 m wide, 3.15 m high room of office building with split hanging air conditioning was used for measurement and simulation. Three walls of the room are connected with the corridor. One wall has an inner window of 1.50M * 1.45M, and the other wall is connected with the adjacent room. The volume of the room is about 37m³. On August 27-28, 2019 and September 9-11, 2019, carbon dioxide was released by dry-ice fire extinguisher (from taxing silicon Industrial Co., Ltd., China) was selected as tracer gas for field measurement by gas tracer concentration attenuation method. It is worth noting that at the initial time, the difference between the carbon dioxide concentration of each measuring point and the indoor average carbon dioxide concentration should be within 10% [9]. In addition, in order to reduce the impact of outdoor wind speed during the measurement process, the window outside the corridor shall be closed to ensure that the wind speed in the corridor is within 0.3m/s. The experimental instrument used is shown in table 1, all data are collected continuously, and the time interval is set to record every 5 seconds.

In this study, the type of the window is Horizontal sliding window, and window size is 1.5m×1.45m, the dimension of the split hanging air conditioning supply outlet and the return air inlet is 0.6m×0.1m and 0.6m×0.2m respectively. Measuring point is arranged in a diagonal arrangement method, five different positions are located at high, which is 1.1 m human respiratory plane, carbon dioxide wireless recorder 2 and the temperature and humidity recording instrument 2 are arranged on a desk and a shelf 1, the recorder 1 and the radio carbon dioxide 3 are arranged on the floor frame upper. To study the ventilation effect of different types of window air-conditioned rooms, and avoid the influence of parameters between each other, keeping the other parameters constant, and varying the position of the air conditioning, window ratio (100%, 75%, and 50%), the window position combination, a total of 18 cases were measured, and measuring points in each case are shown as specific location in figure 1.
At the beginning of each measurement, the window is closed and the air conditioner is running. When the indoor temperature is stable, then CO2 is injected into the room from dry-ice fire extinguisher, until the average CO2 concentration reaches about 1800 ppm, the injection is stopped and a fan in the room operates during about two minutes in order to insure a good mixing of the tracer gas with the indoor air. When the concentration in the room is homogeneous and the concentration values of all CO2 sensors are close, the window is opened. The measurement is stop when the CO2 concentration drops to 500 ppm.

| Type                  | Carbon dioxide recorder | Temperature and humidity recorder | Thermal anemometer |
|-----------------------|-------------------------|----------------------------------|--------------------|
| Number                | WEZY-1                  | WSZY-1                           | Testo 425          |
| Produced by           | Tianjianhuayi Technology Development Co. Ltd. | Testo SE & Co. KGaA           |
| Range (ppm)           | 0—5000 ppm             | -40—100°C, 0—100% RH             | 0—20 m/s          |
| Accuracy              | ±75 ppm                 | 0.1°C, 0.1%RH                    | ±(0.03 m/s + 5 % of reading) |
| Environment dependence| 0°C~+50°C, 10~90%RH     | -2°C~+50°C                       |                    |

3. The mathematical model and numerical simulation

3.1. Numerical simulation

To compare the results of experiments and simulations, the initial conditions of CFD models was determined according to measurements at the beginning. The extended computational domain method was employed to study the airflow from outside to the room. The outer boundaries of the computational domain were extended to be 6.6 m × 6.6 m × 6.6 m, which was demonstrated to be physically far enough that the boundary conditions would not have any effect on the airflow pattern in the room.

Numerical analysis was made for the unsteady, three-dimensional turbulent, incompressible fluid and without the effect of radiation. The fluid properties were determined by Boussinesq approximation as constants except the density which could vary with temperature and concentration. The k-ε model is generally used to describe the flow and heat transfer of the air, and the diffusion and the mixture model for mass transfer of CO2. The standard form of the governing equations includes the continuity equation, momentum equation, energy equation, gas composition equation, as follows:

\[
\frac{\partial}{\partial t} (\rho\varphi) + \text{div}(\rho \vec{u} \cdot \varphi) = \text{div}(\Gamma \varphi \text{grad}\varphi) + S_\varphi \tag{1}
\]

Where \( \varphi \) is a general variable, which can represent variables such as \( u, v, w, T, \Gamma, \) and \( S_\varphi \) are velocity vector, generalized diffusion coefficient and source term respectively.

For mixture model the continuity equation is:

\[
\frac{\partial}{\partial t} (\rho_m \vec{u}_m) + \text{div}(\rho_m \vec{v}_m) = 0 \tag{2}
\]

Where \( \rho_m \) is the mixture density and \( \vec{v}_m \) is the mass-averaged velocity.

The momentum equation for the mixture can be expressed as:

\[
\frac{\partial}{\partial t} (\rho_m \vec{v}_m) + \text{div}(\rho_m \vec{v}_m \vec{v}_m) = -\nabla \rho + \text{div}(\mu_m \nabla \vec{v}_m + \nabla \vec{v}_m^T) + \rho_m \vec{f} + \vec{F} - \text{div}(\sum_{k=1}^{n} \alpha_k \vec{v}_{dr,k}) \tag{3}
\]

where \( n \) is the number of phases, \( \vec{F} \) is a body force, \( \mu_m \) is the viscosity of the mixture and \( \vec{v}_{dr,k} \) is the drift velocity for secondary phase \( k \).

The energy equation for the mixture takes the following form:

\[
\frac{\partial}{\partial t} \sum_{k=1}^{n} (\alpha_k \rho_k E_k) + \text{div} \left( \sum_{k=1}^{n} (\alpha_k \vec{v}_k (\rho_k E_k + p)) \right) = \text{div} (k_{eff} \nabla T) + S_E \tag{4}
\]
where \( k_{eff} \) is the effective conductivity, \( \sum (\alpha_k \rho k E_k) \) is the turbulent thermal conductivity [11].

The boundary conditions are as follows: velocity inlet for air conditioning outlet (\( V = 5 \) m/s, \( T = 297.65 \) K), air conditioning inlet is given as outflow boundary conditions, and the \( \text{CO}_2 \) concentration of air conditioning inlet and outlet are equal, the ambient air velocity and outdoor temperature (\( V = 0.1 \) m/s, \( T = 308.15 \) K). The window is open; the walls, floor and earth are adiabatic boundaries and the other surface are outflow.

### 3.2. Air change rate calculation methodology

To assume that \( V \) is room volume, the window opened time is \( dt \), the amount of ventilation is \( G \cdot dt \), outdoor background concentration of the tracer gas is \( C_{bg} \), the average tracer gas concentration of room is \( C \), \( N \) is the ventilation efficiency. Since the same amount of gas flow into and out of a room, according to the carbon dioxide concentration of the room exchanges, the following equation can be established.

\[
C_{bg} \cdot G \cdot dt - C \cdot G \cdot dt = V \cdot dC
\]

(5)

\[
N = \frac{G}{V}
\]

(6)

After integration was:

\[
t = -\frac{1}{N} \cdot \ln(C_{bg} - C) + a
\]

(7)

When \( t = 0 \), the tracer gas concentration is \( C_0 \):

\[
a = \frac{1}{N} \cdot \ln(C_{bg} - C_0)
\]

(8)

\[
C = (C_0 - C_{bg}) \cdot e^{-Nt}
\]

(9)

From above equations, it can be seen that if the outdoor background concentration of the tracer gas is constant, a multi-point decay curve is plotted by measuring the tracer gas concentration change in the room. The air change rate of each measurement points obtained by using least-square method to fit an exponential decay equation (figure 2), which both \( N \), \( C_0 \), and \( C_{bg} \) are considered as estimated parameters [10].

Since indoor air was in a stable state, when opening the window, indoor and outdoor air exchange begins, the air flow to reach steady state will takes time, during which the concentration of the tracer gas did not follow the variation of the decay curve, so the starting point to be selected need to avoid this time. In this study, the starting point of the decay curve is set when the \( \text{CO}_2 \) concentration reaches 1100 ppm, which is far enough from the transition period (figure 3).

![Figure 2. Calculation of air change rate](image)

![Figure 3. Choice of the measurement period](image)
4. Results and discussion

4.1. Ventilation uniformity at different points in the room
Ventilation uniformity is an important feature for evaluating the effect of natural ventilation on improving indoor air quality [5]. In the initial state, the tracer gas is thoroughly mixed with the indoor air, and the initial value of carbon dioxide is the same at each point in the room. Therefore, we can monitor the change of indoor carbon dioxide concentration after opening the window for natural ventilation, calculate and compare the ventilation efficiency at various points, and evaluate the ventilation uniformity of the air-conditioned room. Table 2 shows the calculation results of ventilation efficiency at various points in the room under different conditions.

The position of the air outlet, the way of opening the window, and the opening degree of the window have a great influence on the uniformity of ventilation at different points in the room. It can be found from case1-2-3 and case2-2-3 that in the same way, the air outlet is directly opposite the window, the ventilation efficiency at each point in the room is similar, and the indoor ventilation uniformity is better. In other cases, the value of ventilation efficiency is low. The ventilation efficiency of P2 and P3 is about the same, and the ventilation efficiency of P1 near the window opening position is obviously higher than that of P2 and P3. When the air outlet is located on the side of the window, the ventilation efficiency at each point in the room is quite different but the ventilation efficiency is high. The P2 measurement point in the middle of the room has the highest ventilation efficiency, the ventilation efficiency of P1 near the window opening position is higher than that of P3 far from the window position, indicating that there is less fresh air at the point far from the window position, the indoor ventilation effect and ventilation uniformity are poor.

In the case of the same position of the air outlet, it can be known from case2-1-3 and case2-2-3 that when the window opening position is close to the middle of the room, the ventilation efficiency is not consistent at each point, the ventilation efficiency is lower at the location far from the window and indoor ventilation is poor. When the window opening position is close to the corner of the room, the ventilation efficiency at each point is approximately the same, the ventilation efficiency value is high, and the indoor ventilation uniformity is better. It can be known from case2-3-3 that when the windows are opened from both sides at the same time, the ventilation efficiency at each point in the room is the smallest, the ventilation efficiency of P2 and P3 is about the same, and the ventilation efficiency of P1 near the window opening position is the highest. It is worth noting that it is not the larger the window opening, the better the ventilation uniformity of the room. The ventilation efficiency at each point in the room is greatly different. The P2 ventilation efficiency is the highest. According to case1-1-1, case1-1-2, and case1-1-3, when the windows are opened at 50% and 100%, the ventilation efficiency at each point is quite different, and the ventilation efficiency of P2 is the highest. The ventilation efficiency of P1 near the window is higher than that of P3 far from the window. When the window is opened at 75%, the ventilation efficiency at each point is similar, and the indoor ventilation uniformity is the best. To select reasonably air outlet position, window opening method and window opening degree are conducive to improve indoor ventilation uniformity and indoor air quality.

Table 2. Air change rate of different cases

| Case    | P1 (h⁻¹) | R²  | P2 (h⁻¹) | R²   | P3 (h⁻¹) | R²   | ACR (h⁻¹) |
|---------|----------|-----|----------|------|----------|------|----------|
| Case1-1-1 | 5.4468   | 0.9761 | 4.8168   | 0.9815 | 3.9096   | 0.9690 | 4.7244   |
| Case1-1-2 | 5.5152   | 0.9803 | 6.5880   | 0.9884 | 6.4116   | 0.9580 | 6.1716   |
| Case1-1-3 | 8.0604   | 0.9729 | 10.5084  | 0.9839 | 6.3504   | 0.9558 | 8.3064   |
| Case1-2-3 | 8.7408   | 0.9723 | 11.7360  | 0.9798 | 7.9704   | 0.9658 | 9.4824   |
| Case1-3-3 | 7.3620   | 0.9796 | 10.3860  | 0.9904 | 8.7624   | 0.9406 | 8.8368   |
| Case2-1-3 | 7.5312   | 0.9761 | 6.6780   | 0.9868 | 5.1552   | 0.9735 | 6.4548   |
| Case2-2-3 | 7.5780   | 0.9808 | 6.3864   | 0.9849 | 6.3288   | 0.9588 | 6.7644   |
| Case2-3-3 | 6.2028   | 0.9863 | 4.7916   | 0.9859 | 4.8276   | 0.9550 | 5.2740   |
4.2. Air change rate in different conditions

In order to study the ventilation efficiency of air-conditioned rooms under different conditions, the average ventilation efficiency of different types of rooms was calculated according to the ventilation efficiency at each point. It can be seen from the last column in table 2. It is not difficult to find that when the air outlet is located on the side of the window, the ventilation efficiency of the room is higher than that when the air outlet is directly opposite the window, and the ventilation efficiency is lowest when the window opening near the room central. When the air outlet is directly opposite to the window and window is opened from both sides the ventilation efficiency is the smallest (figure 4a). If the window is opened near the corner of the room, the room's ventilation efficiency is always the greatest. It can be known from case1-1-1, case1-1-2 and case1-1-3 that the larger the window opening, the higher average ventilation efficiency of the room (figure 4b). Furthermore, results of simulation experiment indicated that higher temperature difference between the indoor and outdoor contributed to faster indoor CO2 exhausted rate (figure 4c). The location of the air outlet, the way of opening the window, the degree of window opening and the temperature difference between indoor and outdoor have a significant effect on the ventilation efficiency of the room.

![Figure 4](image)

Figure 4. Decay curve of different window opening style (a), degree (b) and temperature difference (c) at point 2.

5. Comparison of simulation and experiment

5.1. Carbon dioxide decay curve

Comparison of simulated and measured indoor CO2 concentration of case1-1-3 when indoor and outdoor temperature difference is 10.5 °C to validate the numerical model. Figure 5 shows the simulation and measurement carbon dioxide decay curve. Due to the unavoidable imperfect mixing between indoor air and tracer gas in the beginning of the measurement, the measurement results are a little different to the simulation results. The average error between them is 18.6%, but the trend of CO2 concentration is basically the same. Therefore, the simulation results can correctly reflect objective laws and simulate the air flow situation after opening window.
Figure 5. The carbon dioxide decay curve in simulation and experiment.

5.2. Window-opening effect on indoor environment

Figure 6 shows the dynamic change of heat and mass diffusion in an air-conditioned room from opening the window to reach the steady state. By using CFD method the case which indoor and outdoor temperature difference is 23 degrees in case1-1-3 was simulated. The results show that due to the temperature and CO2 concentration difference between indoor and outdoor, the hot air of less dense and CO2 concentration flows into the room from the upper part of the window and extrudes the cold air with high density and CO2 concentration to the outside from the lower part of the window. The hot air flows along the top of the room and mixes with the cold air inside. After 120 seconds of window opening (figure 6a and 6d), the average indoor temperature is raised about 4.7 ℃, the average CO2 concentration is reduced about 134 ppm. At this time the average indoor temperature continues to rise and the average CO2 concentration continues to fall, the air exchange between indoor and outdoor has not reached steady state. After 485 seconds (figure 6b and 6e), the declining trend of room temperature and CO2 concentration values at each point are similar, the average indoor temperature raised 5.5 ℃ after opening window. Due to normal operation of air conditioning which provide cooling to the room, the average indoor temperature is increased to 22.5 ℃ and no longer rise, and the air exchange between inside and outside have reached approximately to a steady state. At this time, the average indoor CO2 concentration dropped to 1046 ppm, but since the absence of CO2 source and the CO2 concentration in indoor and outdoor still have differences, the average indoor CO2 concentration continued to decline. After 2235 second (figure 6c and 6f), the average indoor CO2 concentrations dropped to 550 ppm which consistent with the outdoor CO2 concentration and almost no longer declining.
6. Conclusions

Opening window in an air-conditioned room can eliminate indoor pollutants, the ventilation effectiveness depends on the ventilation uniformity and ventilation efficiency. With reasonably selected air outlet position, the way and degree of window opening, we can improve indoor ventilation uniformity and ventilation efficiency of the room. When the air outlet is directly opposite the window, the window opening position is close to the corner of the room and the window is opened at about 75%, the indoor ventilation uniformity and ventilation efficiency is the best. Larger window opening and higher temperature difference between the indoor and outdoor contributed to faster indoor CO2 exhausted rate.

There is a time constant for opening window in an air-conditioning room, which effect on the indoor temperature and the concentration of harmful substances. For the cases this paper involved, the time constant is about 30 minutes, different indoor and outdoor temperature difference, room arrangement and the volume of the room have different time constant.

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