Variation of Indoor Airflow Patterns under Dynamic Outdoor Wind Conditions in Large Space Naturally Ventilated Buildings

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Abstract. Understanding Indoor Airflow Patterns (IAPs) helps control air contaminants in large naturally ventilated buildings (NVBs). However, the effect of random and unpredictable changes in outdoor wind conditions (OWC) is a major contributor to the variation in IAPs in the NVBs, making the IAP uncontrollable. This study presents the results of field measurements and numerical simulation in a NBV to study the IAP variation characteristic under the dynamical OWC. The OWC data monitored in real time was processed with Kalman Filtering (KF) and the gradient method to decompose the data prior to being entered into the CFD solver. The trend was similar between the simulated and measured data of a full size NBV. In addition, the distribution of internal turbulence intensity varied widely depending on the spatial locations and time intervals. The variation in speeds in the vicinity of windbreaks greatly affected the variation in IAP on a certain frequency scale. The results not only prove that CFD simulation to be an efficient tool for the prediction of time-averaged IAP, but also initialize efficient measures for the control of IAQ in dynamic OWC of large space NVBs.

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1 Introduction

As a passive ventilation mode, natural ventilation technology is more widely used into practical life and production. The study of natural ventilated airflow patterns includes both interior structure inside building and its surrounding environment, because the effect of which on indoor environment is restricted by the actual outdoor wind conditions (OWC). Natural ventilation plays an important role in improving indoor air quality in large spaces, and affects the comfort level of indoor temperature and humidity fields ([1]). With good natural ventilation, fresh air can be transported into the room, so that the airflow can be effectively circulated ([2]). The random and unpredictable characters of OWC determine that the indoor airflow patterns (IAP) cannot always contribute to the emission of pollutants inside the building. A full understanding of IAP can aid in the control of contaminants within large spaces naturally ventilated buildings (NVBs). Therefore, it is particularly important to study the variation characteristics of IAP under dynamical OWC.

The high-frequency variation of outdoor wind speed makes the in-situ raw data complex ([3]). The interaction of high turbulent flow with indoor and outdoor airflow makes the IAP uncontrollable. Changing variations of wind fields make the research challenging. At tiny time scales, the fluctuation of wind speed is highly related to the frequency. It is necessary to capture the variation characteristics of outdoor wind speed under fluctuating conditions ([4]).

The purpose of this paper was to use statistical methods to analyse the outdoor in-situ wind speed data, and to reveal the characteristics of fluctuation behaviour from the complex raw data. At the same time, combined with the CFD method and experimental results, we studied the changing of IAP under the dynamical OWC.

2 Method

Statistical methods help to extract dynamic wind speed variation laws. Noise impurities can be effectively filtered out through appropriate filtering methods. In this paper, the Mann-Kendall (M-K) method can help to analyse the variation of outdoor in-situ wind speed.

2.1 Basic details of a naturally ventilated building

Fig. 1 shows the layout of indoor measuring points in a NVB. The arrows indicate the direction of the windward side. Different measuring points (12 points) distributed in different spatial positions. This building has a typical pitched roof with three openings. Measuring point A is closer to the windward opening, and there are also measuring points on the leeward side, and more inside the building. In addition, an in-depth study of the airflow at location A was performed.

2.2 Basic characteristics of natural wind

Natural winds are complex and random over time and space. Therefore, it is necessary to collect instantaneous wind speed information. Instantaneous wind speed includes average wind speed and fluctuating wind speed ([5]). Moving average method is very useful for studying average wind speed. It can divide time into different stages and average the sampled data to reflect the overall information to a greater extent. However, the strong fluctuation makes the analysis results of instantaneous wind speed affected by noise of wind speed. A variety of filtering methods can solve the problem of signal noise ([6]).

2.3 Mann-Kendall method

The Mann-Kendall (M-K) test method is useful for analyzing time series for mutation and trend prediction ([7]). A long-term time series contains a large amount of information. With the help of the M-K test, the calculation process becomes simple, and the mutation time area can be visually displayed to obtain the overall change. Two standard statistical analysis quantities, UF and UB, are defined. By comparing the two statistical analysis quantities of the sampling statistics, the upward or downward trend of the data set can be obtained accordingly. UF>0, showing an upward trend; UF<0, showing a downward trend; UF and UB have an intersection, and the corresponding mutation begins to appear.

3 Results

By combining field test and CFD simulation results, the study found that the average overall difference between measurements and simulations was small. The research results intuitively give the characteristics of wind speed series and the results of M-K test, which is convenient for analyzing the variation characteristics of wind speed data in the time-frequency domain.

3.1 Wind speed characteristics

Fig. 2 shows the statistical distribution of wind speed data. The in-situ test time is April 17, 2014 0:00:00-23:59.59. With a time span of hours, the distribution of the average wind speed in each hour is actually very similar to the original wind speed (after denoising), so it can be seen that the moving average method has applicability in dealing with the characteristics of outdoor wind speed changes. However, the hourly
averaged results lead to the expansion of the time domain, with too little information about wind speed changes, and more difficult feature extraction for the wind speed series. Therefore, this study takes 10 min as time span within the research scope.

Fig. 2. Time series diagram of natural wind speed data.

Fig. 2 is the comparison of the wind speed data for the first 10 minutes of each hour versus wind speed data includes full minute of each hour. The error between the two methods is 12.9%. Thus, taking 10 minutes as the research scope of wind characteristics not only ensures the reliability of the overall macroscopic information, but also contains enough details of wind speed changes. It can be found that the outdoor wind speed is low in the early morning. In order to better show the characteristics of wind speed, the data with larger wind speed from 12:00-12:10 at noon was selected for subsequent analysis.

3.2 Probability distribution of wind speed series

There is no heat source in the selected naturally ventilated building, and there is no heating during the experiment. Therefore, the airflow organization is completely generated by the action of wind pressure. In order to study the impact of outdoor natural wind on indoor airflow pattern, we need to focus on the essential characteristics of outdoor wind speed. Fig. 3 shows the distribution of the outdoor wind speed components (u and v) in two directions from 12:00 to 12:10. Where, the velocities (u and v) we chose are two components of the windward plane perpendicular to the building. The results show that the outdoor natural wind presents typical normal distribution characteristics. By observing the distribution of the original data, the measured wind speed data has the characteristics of high-frequency and low-amplitude fluctuations, and the data is numerous and chaotic. Through statistical analysis, the probability density of outdoor wind with complex motion also satisfies the normal distribution characteristics.

![Fig. 3. Probability density of natural wind speed data during 12:00-12:10.](image)

3.3 Denoising of wind speed

Fig. 4 shows the original wind speed profile after Kalman filtering (KF) ([8]) from 12:00 to 12:10. By filtering the noise signal, the overall wind speed dynamic trend is obtained from the complex raw field data. The trend of the filtered swing signal is consistent with the original signal, which is more intuitive. In addition, the horizontal and vertical sections of the naturally ventilated building calculated by numerical simulation are given at the four extreme positions in Fig. 4 (63s, 260s, 474s and 575s from 12:00, respectively), reflecting the influence of OWC on indoor air distributions.

![Fig. 4. Filtering results of natural wind data during 12:00-12:10.](image)
3.4 Variation trend of wind speed

Fig. 5 shows the results of the M-K test method in the selected time range 12:00-12:10. Fig. 5 (a) represents the test result of outdoor wind, and Fig. 5 (b) represents the test result of windward measuring point A. It can be seen from Fig. 5 (a) that the outdoor wind speed increases first and then decreases, continues to rise, and finally shows a slight downward trend. On the whole, the wind speed is on the rise. Because value of UF is outside the 0.5 confidence interval, the overall change is dramatic. Corresponding to the large actual noon time, the wind speed varies greatly. It can be seen from the Fig. 5 (b) that the wind speed at the measuring point also presents a large upward trend, but the changing trend is not obvious at first, and then it shows a significant upward trend with a slight decrease. Overall, the changing trends of outdoor wind data and measurement points data are consistent. Considering that the indoor measurements are affected by the building envelope, the indoor test results are not as significant as the outdoor test results.

![M-K test chart of natural wind data during 12:00-12:10.](image)

Fig. 5. M-K test chart of natural wind data during 12:00-12:10.

4 Discussions and conclusions

In order to analyse the change rule of airflow distribution of NVB, this paper focuses on the change of exterior wind speed data, and deeply verifies the influence of outdoor field on indoor field.

1. Outdoor wind speed data has the characteristics of high-frequency variations. With the help of filtering method and turbulence idea, the overall trend of wind speed change can be qualitatively judged.

2. The indoor flow field has different variation rules under different outdoor wind speed conditions, which is related to the different positions of the indoor flow field and is affected by the distance from the outdoor openings.

3. The numerical simulation model has been verified by experimental test data, which has wider research significance for analyzing different wind speed modes.

4. Through the M-K test, the time span of the indoor flow field state changes which caused by the changing outdoor wind speed conditions can be quantitatively analysed. The trigger mechanism and trigger time are studied within the research range of time, and compared with the experimental data to discuss the correctness of the corresponding time.

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