An experimental study on concentration field reconstruction of indoor pollutant based on mobile monitoring

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Abstract: Concentration field reconstruction (CFR) refers to the use of the collected spatio-temporal discrete concentration data to reconstruct the concentration field that can reflect the spatio-temporal distribution of pollutants according to certain rules, which is of great significance to ensure the safety of indoor environment. In this paper, using alcohol as the release source, and the field reconstruction experiment based on mobile robot is carried out in an environmental chamber with two types of ventilation: side-up-supply-and-side-down-return, and top-supply-and-side-down-return. Using the experimental data, the performance of Kernel DM+V/W+ method is compared with the other two internationally recognized Kernel DM+V method and Kernel DM+V/W method in field reconstruction and source location from the perspective of qualitative and quantitative. The comparison results show that the Kernel DM+V/W+ method not only has better field reconstruction performance, but also has better source localization performance.

1 Introduction

The indoor environment is the main place where people work and live, and the time spent in it accounts for 80% to 90% of the day[1]. Good indoor air quality is essential to ensure the health of the people in the room and efficient productivity.

Concentration field reconstruction (CFR) refers to use the collected spatio-temporal discrete concentration data to reconstruct the concentration field, which can help us obtain the distribution of indoor air pollutants and provide technical support to ensure air quality. The Kernel series method[2–5] is one of the most well-known CFR methods. It is a model-free method[6], so there is no need to simplify the boundary conditions during the experiment like other model-based methods[7–9]. The Kernel series of methods mainly include the Kernel DM+V method[4] which does not consider the effect of airflow on the concentration field and the Kernel DM+V/W method[5] which considers the effect of airflow on the concentration field.

Kernel DM+V/W does not take into account the inconsistency of the upwind and downwind concentrations affected by airflow, which leads to inconsistency to the actual situation. In order to solve the shortcomings of the Kernel DM+V/W method, our team proposed the Kernel DM+V/W+ method in the preliminary work. Based on the Kernel DM+V method, this method introduces an airflow correction term to describe the difference of the sampling data on the upwind and downwind regions, and the field reconstruction performance of the Kernel DM+V/W+ method is preliminarily verified in the previous work.

The main objective of this paper is to compare and analyze the source localization and field reconstruction performance of Kernel DM+V, Kernel DM+V/W, and Kernel DM+V/W+ methods in real experimental scenarios with two types of ventilation from both qualitative and quantitative perspectives. Alcohol was used as a source, and field reconstruction experiments were conducted under two different types of ventilation: side-up-supply-and-side-down-return, and top-supply-and-side-down-return.

2 Proposed methods

2.1 CFR method introduction

The Kernel DM+V method is suitable for windless environments. Its principle is to spatially extrapolate the sampled data to obtain the concentration values at the unsampled location by weight function (Eq. 1).

However, airflow has an important influence on the spatial distribution of pollutants. The Kernel DM+V/W method describes the effect of airflow on concentration field by stretching the Gaussian kernel along the

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airflow direction[5] without taking into account the difference of pollutants on the upwind and downwind regions under the action of airflow micelles.

Our team has proposed the Kernel DM+V/W+ method in the preliminary work to improve the shortcomings of Kernel DM+V/W. The Kernel DM+V/W+ method introduces an airflow correction term $\vec{F}$ (Eq. 2) to model the difference in the impact of the sampled data on the upwind and downwind regions, so that the impact of the sampled data on the downwind region is greater than that of the upwind region. The calculation process is shown in Eq. 3.

$$\omega_i^{(k)}(\sigma_0)=\frac{1}{\sqrt{2\pi}\sigma_0}\mathrm{e}^{-\frac{\left|x_i-x^{(k)}\right|^2}{2\sigma_0^2}} \tag{1}$$

$$\vec{F}=1+\beta\times\left|\vec{\mu}\right|\times\cos\theta \tag{2}$$

$$\omega_i^{(k)}(\sigma_0)=\frac{1}{\sqrt{2\pi}\sigma_0}\mathrm{e}^{-\frac{\left|x_i-x^{(k)}\right|^2}{2\sigma_0^2}}\cdot(1+\beta\times\left|\vec{\mu}\right|\times\cos\theta) \tag{3}$$

Where σ_0 is the Kernel width of the weight function; x_i is the coordinate of the grid center where the sample location is located; x_k is the coordinate of the k$^{\text{th}}$ grid center near the sampling location; β is the wind speed influence factor; $\vec{\mu}$ is the wind speed vector; θ is the angle between the line of x_i, x_k and the wind direction.

2.2 Quantitative evaluation system

Since the real concentration distribution is difficult to observe with the naked eye, the reconstructed concentration field cannot be directly compared with it. Therefore, the average negative logarithm predictive density (NLPD), which has been widely used in previous studies[4,5], was used to quantitatively evaluate the performance of the three CFR methods.

The dataset is randomly divided into the training set D_{train} and the testing set D_{test}. The CFR is performed using the data in the training set D_{train}, and the data in the testing set D_{test} are used as the comparison benchmark. Then, NLPD (Eq.4) is used to calculate the difference between the reconstructed concentration field and the real concentration field. The smaller the NLPD value, the more accurate the reconstructed concentration field.

$$NLPD\approx\frac{1}{2n}\sum_{i\in D}\left\{\log\hat{v}(x_i)+\frac{\left(r_i-\hat{r}(x_i)\right)^2}{\hat{v}(x_i)}\right\}+\frac{1}{2}\log(2\pi) \tag{4}$$

Where, r_i is the data in the testing set; $\hat{v}(x_i)$ and $\hat{r}(x_i)$ are the concentration variance and mean concentration calculated by the CFR method, respectively.

3 Experimental setup

3.1 Design and construction of Mobile robot

In this experiment, a mobile robot was built to collect environmental parameter information (Fig. 1). The robot is equipped with three layers of sensors with heights of 0.5 m, 0.8 m and 1.1 m respectively. Each layer contains an alcohol sensor, an anemometer, and a temperature and humidity sensor. This study only takes the alcohol concentration data collected at the height of 0.8 m as the research object. The selected alcohol sensor can detect the concentration in the range of 10~500 ppm, and its response time is less than 2 s, and its recovery time is less than 4 s.

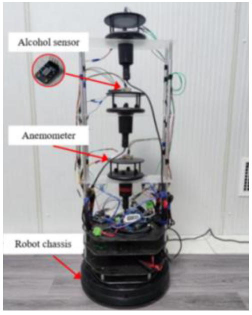


Fig. 1 Mobile Robot

3.2 Experimental conditions

This experiment was carried out in an environmental chamber located in Nanjing Tech University with a size of 6 m (length) × 5 m (width) × 3.5 m (height), which can adjust various ventilations forms. The robot was limited to move in an area of 4 m × 3 m.

In this experiment, alcohol vapor was used as the release source, which was obtained by heating a 95% alcohol solution in a constant temperature water bath. The source was set at a height of 0.8 m. The alcohol source and experiment site are shown in Fig. 2 and Fig. 3, respectively.

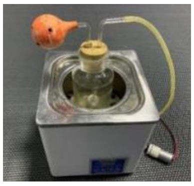


Fig. 2 Alcohol source

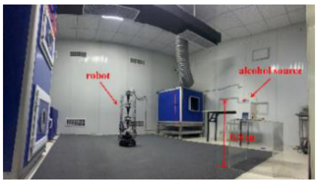
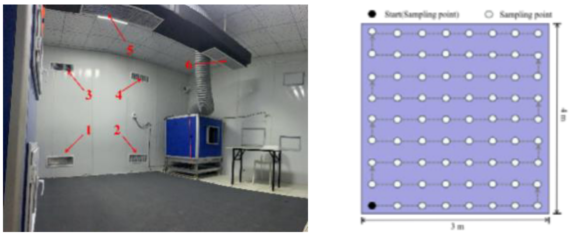


Fig. 3 Experiment site

Two types of ventilation were used in the experiment: side-up-supply-and-side-down-return and top-supply-and-side-down-return. The location of the outlets is shown in Fig. 4(a). In the type of side-up-supply-and-side-down-return, the outlets are 1 and 2, and the inlets are 3 and 4; in the type of top-supply-and-side-down-return, the inlets are 5 and 6, and the outlets are 1 and 2. During the experiment, the mobile robot collected environment information along a trajectory with 72 sampling points for 8 laps, and the robot stayed for 10 s at each sampling point. At the beginning of the experiment, the robot and the alcohol source device started at the same time. The movement trajectory of the robot and the location of the sampling point are shown in Fig. 4(b).



(a) (b)

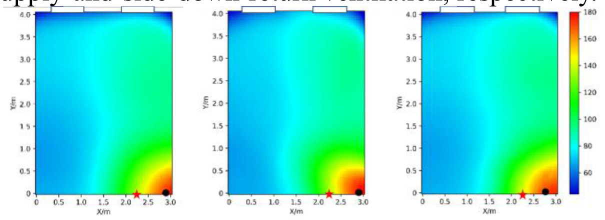
Fig. 4 Inlets, outlets and robot trajectory: (a)outlets: 1, 2; inlets: 3, 4, 5 and 6; (b) Robot trajectory

4 Experimental results

4.1 Qualitative evaluation

4.1.1. Evaluation of CFR

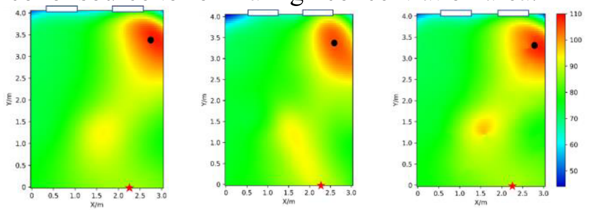
This paper uses the data collected by the mobile robot to reconstruct the concentration field. Fig. 5 and Fig. 6 show the results of three CFR methods in the side-up-supply-and-side-down-return ventilation and the top-supply-and-side-down-return ventilation, respectively.



(a) Kernel DM+V (b) Kernel DM+V/W (c) Kernel DM+V/W+

Fig. 5 Mean concentration maps reconstructed by three CFR methods under the condition of side-up-supply-and-side-down-return ventilation (The pentagram is the location of the alcohol source, The dot is the maximum value of the mean concentration, see Fig. 4 for details)

According to the Fig. 5, the mean concentration maps of three methods are basically consistent. The high concentration areas are concentrated close to the source. Under this ventilation form, the alcohol continues to diffuse towards the exhaust outlet, so that most of the alcohol gas accumulates on one side of the alcohol source to form a high concentration area.



(a) Kernel DM+V (b) Kernel DM+V/W (c) Kernel DM+V/W+

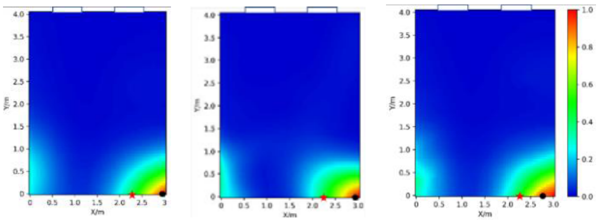
Fig. 6 Mean concentration maps reconstructed by three CFR methods under the condition of top-supply-and-side-down-return ventilation

According to Fig. 6, when the ventilation form is set to top-supply-and-side-down-return, the high-concentration areas in the reconstructed concentration field by CFR method are mainly concentrated in the upper right corner of the experimental site. In addition, there is a concentration extreme value area near the upper inlet. It can be inferred that the alcohol vapor is continuously diffused towards the outlet due to the dilution and transportation of the air flow, and accumulates near the outlet to form a high concentration area. Only a small part of alcohol vapor accumulates locally under the entrainment of the supply air flow to form a sub concentration area.

4.1.2. Evaluation of source localization

Under the condition of side-up-supply-and-side-down-return ventilation, the locations of the maximum concentration in the concentration field reconstructed by Kernel DM+V/W+ method (0.25 m) is closer to the location of the real source than Kernel DM+V method (0.7 m) and Kernel DM+V/W method (0.7 m). It means that the Kernel DM+V/W+ method has better source localization performance. Under the condition of top-supply-and-side-down-return ventilation, the locations of the maximum concentrations in the concentration field reconstructed by three CFR methods are all far away from the location of real alcohol source (Kernel DM+V: 3.42 m, Kernel DM+V/W: 3.47 m, Kernel DM+V/W+: 3.25 m). Even so, the Kernel DM+V/W+ method still performed better than the other two CFR methods. But it also shows that relying solely on the maximum value is not sufficient to locate the source.

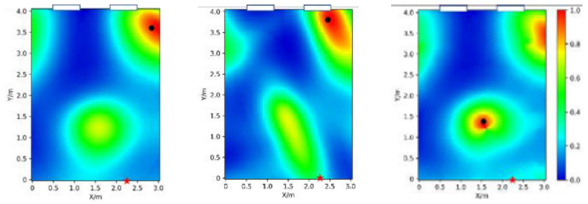
In previous study[4], the concentration variance map is proved to have good source localization performance. In this paper, we further reconstructed the concentration variance maps by the three CFR methods under two types of ventilation (Fig. 7 and Fig. 8) to explore the localization performance of three CFR methods.



(a) Kernel DM+V (b) Kernel DM+V/W (c) Kernel DM+V/W+

Fig. 7 Concentration variance maps reconstructed by three CFR methods under the ventilation in the form of side-up-supply-and-side-down-return

The locations of the maxima variance in the concentration variance maps of three CFR methods in Fig. 7 are basically consistent with the locations of the maximum concentration in Fig. 5. It also shows that the distance between the position of maximum value in the concentration variance map reconstructed by Kernel DM+V/W+ and the source is smaller than Kernel DM+V and Kernel DM+V/W.



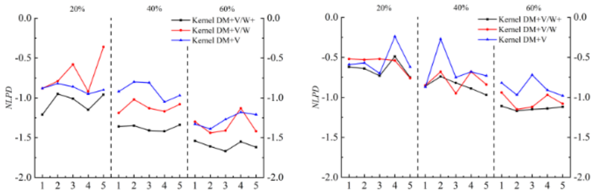
(a) Kernel DM+V (b) Kernel DM+V/W (c) Kernel DM+V/W+

Fig. 8 Concentration variance maps reconstructed by three CFR methods under the condition of top-supply-and-side-down-return ventilation

It can be seen in Fig. 8 that under the condition of top-supply-and-side-down-return ventilation, the maximum value of the concentration variance calculated by the Kernel DM+V/W+ method is the closest to the real source (1.31 m). This result proves that the Kernel DM+V/W+ method has better source localization performance.

4.2 Quantitative evaluation

In this study, the NLPD was used to quantify the performance of three CFR methods. The collected concentration data were randomly divided into D_{train} and D_{test} according to sampling ratios of 20%, 40% and 60% (the ratio of training set to overall data), and each sampling ratio was randomly assigned five times. Fig. 9 shows the NLPD of three methods.



(a) (b)

Fig. 9 NLPD of three CFR methods under two ventilation forms: (a) side-up-supply-and-side-down-return ventilation; (b) top-supply-and-side-down-return ventilation

Based on the NLPD of three CFR methods under two ventilation forms, when the sampling ratio is low (20%), the NLPD values of three methods fluctuate greatly, and the performance of field reconstruction is poor. When the sampling ratio increases, the NLPD values and its fluctuation of are also decreasing. The NLPD value and fluctuation amplitude of Kernel DM+V/W+ are the smallest in each sampling ratio, which indicates that the improved method can better reflect the real concentration field information after distinguishing the different influences on the upwind and downwind regions.

Comparing the NLPD of three CFR methods under two ventilation conditions, Kernel DM+V/W+ does not always have the best quantitative performance at each sampling ratios under the condition of the top-supply-and-side-down-return ventilation, which is different from that under the condition of the side-up-supply-and-side-down-return ventilation. The possible reason is that the ventilation form of top-supply-and-side-down-return has the dominant air flow in the vertical direction, while the air flow in the horizontal direction is relatively weak. This type of airflow brings a great challenge for the Kernel DM+V/W+ method to reconstruct the concentration field in the horizontal direction.

5 Conclusions

In this paper, Kernel DM+V, Kernel DM+V/W and Kernel DM+V/W+ were used to reconstruct the alcohol concentration field under two types of ventilation: side-up-supply-and-side-down-return and top-supply-and-side-down-return. And the performance of three CFR methods in reconstructing concentration field and locating pollution source is evaluated quantitatively and qualitatively. The research results show that the Kernel DM+V/W+ method proposed by our team is better than the other two methods. The specific conclusions are as follows:

(1) Increasing the sampling ratio (the ratio of training set to overall data) can effectively improve the performance of the CFR method.
(2) In both ventilation conditions, the Kernel DM+V/W+ method is superior to Kernel DM+V and Kernel DM+V/W methods. Therefore, when reconstructing the concentration field, considering the influence difference of the sampling data on the upwind and downwind regions can effectively improves the performance of the CFR method.
(3) From the quantitative results of the two ventilation modes, it can be seen that the Kernel DM+V/W+ method is not suitable for the flow field environment with vertical dominant airflow.

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