Simulation of Formaldehyde Distribution Characteristics under Different Indoor Conditions and Optimization of Monitoring Methods

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Abstract. The distribution of indoor formaldehyde concentration is affected by many factors, which makes the concentration distribution of formaldehyde in different indoor positions uneven, which has a negative impact on the monitoring accuracy. Firstly, through orthogonal experiment and numerical simulation, it is determined that the airflow organization and the location of pollution source have a great influence on the monitoring accuracy. Further research found that the relative position of the air supply airflow and the pollution source affected the diffusion of formaldehyde in the room. Through Computational Fluid Dynamics(CFD) simulation, the error and correction basis of the monitoring data caused by different monitoring conditions were obtained. Finally, the accurate optimal monitoring position is given by genetic algorithm optimization. In the optimization process of 17 working conditions, 76% of the working conditions only need one sensor and correction, which can make the monitoring effective coefficient λ reach more than 80%, and 24% of the working conditions need two sensors.

1. Introduction

With the development of urbanization in China, many houses have been built and renovated, and the resulting large-scale decoration has led to serious formaldehyde pollution problems, which have a serious impact on the health of residents. Siddiqui et al.[1] used Computational Fluid Dynamics(CFD) to study the trajectory of chemical pollutant diffusion in the room. Jurelionis et al. [2] studied the effects of indoor ventilation on the distribution of particulate matter and aerosol, respectively. Chen and Wen[3-5] conducted a lot of research on the design of indoor air quality monitoring network, selected the best airflow model, and compared the advantages and disadvantages of multi-region model and CFD model in sensor network design. Abbassi et al.[6] used CFD to simulate the distribution of natural gas when natural gas leaks at home. Adelikhah et al.[7] adopted CFD technology to study the indoor radon distribution law of typical naturally ventilated rooms under two scenarios (when the door is closed and opened). Cheng et al.[8] adjusted the boundary conditions according to the significance of the influence factors on the multi-region CFD model to improve the accuracy of the simulation. Fontanini et al.[9] studied the optimal position of sensors for indoor air quality and virus transmission in public places by using an algorithm based on Markov matrix, and considered the constraints of sensor placement. Kyriacou et al.[10] developed a special MATLAB toolbox to select the appropriate monitoring location for pollutant monitoring. Cheng et al.[11] developed a method to optimize the location of temperature and carbon dioxide sensors for thermal comfort and indoor air quality monitoring in multi-zone environments with limited field measurements, supported by BIM technology based on genetic algorithms.

There are few studies on the CFD simulation of multi-factor affecting indoor formaldehyde distribution and the optimal location of formaldehyde sensor layout. This paper selects the factors that have a greater impact on the indoor distribution to design orthogonal experiments, and uses CFD technology to simulate the distribution characteristics of formaldehyde under different working conditions. Based on the genetic algorithm, the optimal location and number of formaldehyde sensors are obtained, and the monitoring effective coefficient λ is selected to evaluate the effectiveness of the monitoring data to form a sensor layout strategy.

2. Research methods

2.1 CFD simulation

The experimental room is an office that has undergone the process of painting walls, replacing floor tiles, ceilings, furniture and air conditioning systems. The experimental room adopts the air distribution of upper

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supply and upper return. The room plan is shown in figure 1. In this paper, CFD simulation is used to study the factors that affect the results of pollutant monitoring.

2.2 Orthogonal experimental design

Combined with other research and investigation[1-3], this paper preliminarily determines six influencing factors, which are air distribution(Up-supply and up-return , Side delivery , displacement ventilation, Split wall hanging air conditioning, Split cabinet air conditioning ,respectively), room area(25 m2,45 m2,65 m2,respectively) room length-width ratio(1:1,1.5:1,2:1, respectively), air change rate(5 h-1,7.5 h-1,10 h-1, respectively), pollution source location(room center, room side, vent, respectively), and pollution source intensity(2.34×10-10kg/s, 4.68×10^{-10}kg/s, 7.02×10^{-10}kg/s, respectively). Through CFD simulation of multi-level combination conditions, the influence degree of different factors on formaldehyde concentration distribution is obtained. According to the analysis of variance, the air distribution and the location of the pollution source have a significant effect on the distribution of formaldehyde concentration, and the influence of the air distribution is greater than that of the pollution source. The influence of room area, room aspect ratio, ventilation frequency and pollution source intensity on the results is not significant.

In order to further study the influence of air distribution and pollution source location on the distribution of formaldehyde concentration, a real room was taken as the research object, different air distribution and pollution source locations were set, and the average concentration of the room was taken as the target concentration to simulate the combination of air distribution and pollution source location. The detailed working conditions are shown in table 1. The schematic diagram of different pollution source locations is shown in figure.2.

Table 1. Simulation condition table

location of pollution	Air distribution	Operating condition	Optimal number of
location of pollution source 1 (L1)	Up-supply and up-return(grille) (MV1)	case_1	2
	Up-supply and up-return(diffuser) (MV2)	case_2	1
	Side delivery (SV)	case_3	1
	displacement ventilation(DV)	case_4	1
	Split wall hanging air conditioning (AC1)	case_5	2
	Split cabinet air conditioning (AC2)	case_6	1
location of pollution source 2 (L2)	Up-supply and up-return(grille) (MV1)	case_7	1
	Up-supply and up-return(diffuser) (MV2)	case_8	1
	Side delivery (SV)	case_9	1
	displacement ventilation (DV)	case_10	2
	Split wall hanging air conditioning (AC1)	case_11	1
	Split cabinet air conditioning (AC2)	case_12	1
location of pollution source 3 (L3)	Up-supply and up-return(grille) (MV1)	case_13	1
	Up-supply and up-return(diffuser) (MV2)	case_14	1
	displacement ventilation (DV)	case_15	2
	Split wall hanging air conditioning (AC1)	case_16	1

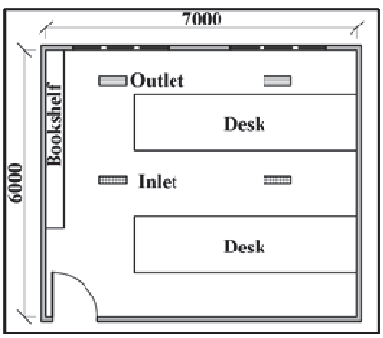

Figure 1. Experimental room floor plan

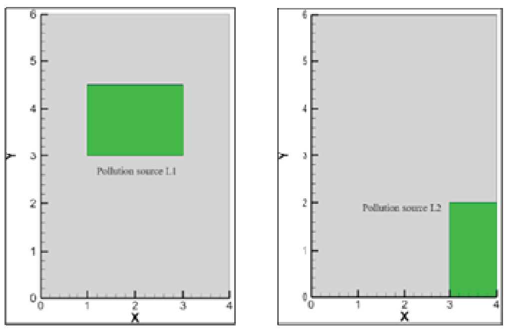

Figure 2. Location of pollution source

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2.3 Optimization of monitoring method based on genetic algorithm

In this paper, the optimization problem is regarded as a single objective optimization problem. In the single objective optimization problem, the purpose of solving the problem is to improve the unique index, and the minimum or maximum value reflects the optimization degree of the sensor layout. The objective function is shown in Eq.(1) and (2).

$$f(a)=\sum_{i=1}^{n} g_i(a) \tag{1}$$

$$g_i(a)=\begin{cases}1, |a-c_i|\le\varepsilon \\ 0, |a-c_i|>\varepsilon\end{cases} \tag{2}$$

Table 2. Constraints on c_i and a

Position	Coordinate range
c_i (The whole room)	$0.5\le X\le 3.5, 0.5\le Y\le 5.5, 0.5\le Z\le 2.4$
c_i (Respiratory area)	$0.5\le X\le 3.5, 0.5\le Y\le 5.5, 0.5\le Z\le 1.5$
a	$0\le X\le 0.05$ or $3.95\le X\le 4$ or $0\le Y\le 0.05$ or $5.95\le Y\le 6$ or $2.85\le Z\le 2.9$

In the formula, a is the formaldehyde concentration at a point near the wall.The formaldehyde concentration monitored by the sensor in practice, mg/m3. c_i is the formaldehyde concentration at a point in the target area, mg/m3. n is the number of points in the target area, that is, the number of c_i .The value range of a point near the wall and a point in the target area is shown in Table 2.

ε is the allowable error between the monitoring data and the formaldehyde concentration at a certain point in the target area, mg/m3. When the error is within the allowable error range, when the error exceeds the allowable error range. Finally, we used Eq.(3) to describe Effectiveness of sensor monitoring.

$$\lambda=\frac{f(a)}{n} \tag{3}$$

3. Research Results and Analysis

3.1 Influence of air distribution on formaldehyde distribution characteristics

The form of air conditioning system determines the indoor air flow organization, thus affecting the distribution of pollutants. The monitoring data of sensors attached to random positions may not reflect the indoor pollution level well. Through CFD simulation of formaldehyde distribution characteristics under different airflow organizations, the monitoring data under different working conditions can effectively reflect the indoor pollutant level. The monitoring data of formaldehyde on different walls and the average concentration of formaldehyde in the room are shown in table 3.

Take the ventilation mode of up-supply and up-return (grille) as an example, the simulation results are shown in figure 3. The formaldehyde concentration in the central area of the room is higher than that near the wall. The data can more obviously reflect the difference of formaldehyde concentration near the center and wall of the room, which will bring a large error to the monitoring data of the sensor. Among them, if the sensor is arranged on the side wall, the difference between the monitoring data and the main pollutant concentration index of the room is the largest, and the difference is slightly smaller when arranged on the ceiling. Both need to correct the monitoring data.

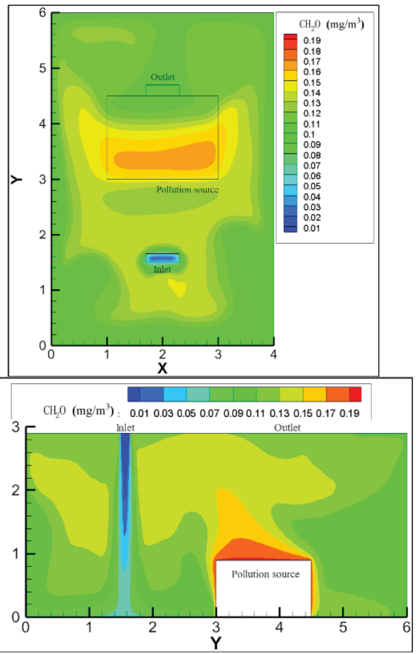

Figure 3. Formaldehyde concentration of z=1.4m and x=sections（MV1，L1）

3.2 Influence of pollution source location on formaldehyde distribution characteristics

The pollution sources are located in the center of the room, and the air supply flow does not directly act on the pollution sources. The formaldehyde emitted by the pollution sources diffuses in different directions under the drive of the air flow. This section will simulate the location of other pollution sources, like the pollution source is located in the corner of the room, where the air supply airflow is not effective, and the pollution source is near the air supply outlet, and the air supply airflow directly acts on the pollution source. In addition to the location of the pollution source, the other conditions are exactly the same as Section 3.1. The formaldehyde monitoring data of different walls and the average concentration of formaldehyde in the room are shown in table 3.

Table 3. Monitoring data of different wall surfaces and room average values (L1 L2 L3)

		MV1	MV2	SV	DV	AC1	AC2
L1	C	0.119	0.115	0.12	0.136	0.126	0.132
	E	0.104	0.098	0.124	0.127	0.115	0.128
	N	0.106	0.12	0.1137	0.122	0.10	0.114
	S	0.104	0.1	0.127	0.13	0.108	0.129
	W	0.104	0.129	0.118	0.138	0.114	0.132
	c_a	0.128	0.124	0.131	0.141	0.136	0.141
L2	C	0.089	0.082	0.074	0.065	0.075	0.109
	E	0.096	0.102	0.072	0.064	0.08	0.108
	N	0.069	0.081	0.058	0.05	0.057	0.094
	S	0.092	0.096	0.089	0.056	0.078	0.116
	W	0.075	0.067	0.06	0.043	0.061	0.115
	c_a	0.086	0.082	0.068	0.075	0.076	0.117
L3	C	0.164	0.117		0.129	0.144	
	E	0.162	0.107		0.106	0.137	
	N	0.163	0.112		0.117	0.141	
	S	0.161	0.125		0.133	0.137	
	W	0.167	0.123		0.126	0.147	
	c_a	0.162	0.125		0.137	0.151	

Take the ventilation mode of up-supply and up-return (grille) as an example, the simulation results are shown in figure 4 and figure 5. The formaldehyde concentration near the ceiling is between the side wall near the pollution source and the side wall not close to the pollution source, and the formaldehyde concentration in the vertical direction is no longer significantly different. If the sensor is installed on the ceiling, the monitoring data is close to the average concentration of the room and the average concentration of the personnel breathing zone. If the sensor is installed on the side wall near the pollution source, the monitoring data value is large. Otherwise, it is smaller and needs to be corrected.

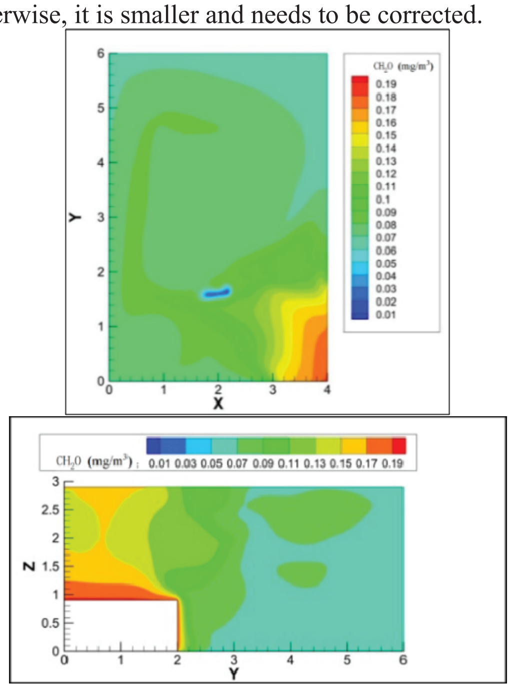

Figure 4. The formaldehyde concentration of z=1.4m and x=3 sections（MV1，L2）

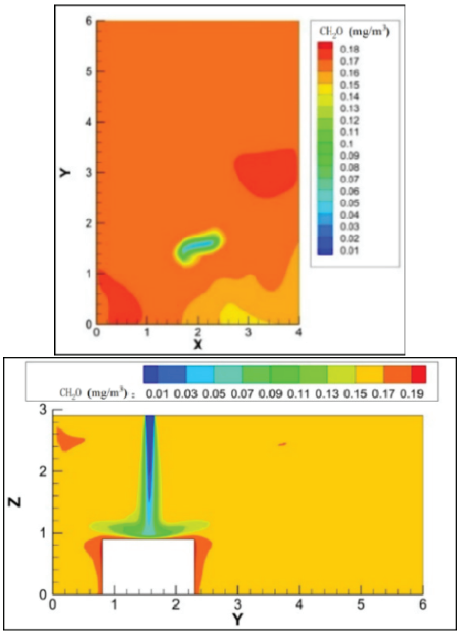

Figure 5. The formaldehyde concentration of z=1.4m and x=2 sections（MV1，L3）

3.3 Analysis of genetic algorithm optimization results

The genetic algorithm is realized by the genetic algorithm toolbox in MATLAB. The requirement of the effective coefficient is set to 0.8, this method is used to solve all working conditions. The optimal solution of the sensor arrangement under different conditions is shown in table 4. Case_1 to case_16 are the various working conditions involved. In most cases, one sensor is arranged to correct the monitoring data to meet the requirements of the effective coefficient. Only in a few cases, two sensors need to be arranged to meet the requirements of the effective coefficient.

Table 4. Optimization of formaldehyde sensor layout results

	Optimal number of sensors	1)	2)	3)
case_1	2	0.5	0.65	0.81
case_2	1	0.58	0.84	
case_3	1	0.7	0.83	
case_4	1	0.6	0.81	
case_5	2	0.41	0.52	0.88
case_6	1	0.63	0.91	
case_7	1	0.76	0.83	
case_8	1	0.88		
case_9	1	0.9		
case_10	2	0.37	0.61	0.93
case_11	1	0.74	0.9	
case_12	1	0.67	0.82	
case_13	1	0.9		
case_14	1	0.62	0.82	
case_15	2	0.67	0.71	0.95
case_16	1	0.72	0.89	
case_17	1	0.72	0.85	

Case_17 optimizes the sensor layout for the experimental room. The indoor formaldehyde concentration distribution and the optimal sensor placement are shown in figure 6 and figure 7. In the actual room, the optimal formaldehyde monitoring effect can still be achieved through a formaldehyde sensor and the correction of the monitoring data. The coordinates of the best monitoring position are (1.122,4.309,2.855).The results show that further research by genetic algorithm solution can give accurate optimal monitoring position. In the optimization process, priority should be given to improving the monitoring effectiveness by correcting the monitoring data. When the corrected monitoring data cannot meet the requirements, the number of sensors should be increased to improve the monitoring effectiveness. The monitoring effective coefficient λ and the economy can be used to formulate the strategy of optimal sensor placement.

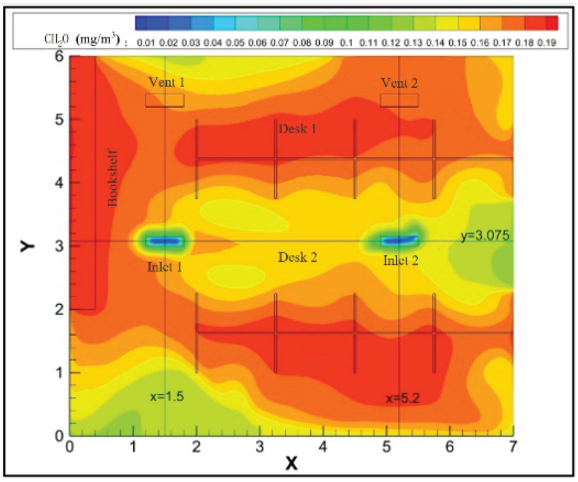

Figure 6. result of z=1.4m sections

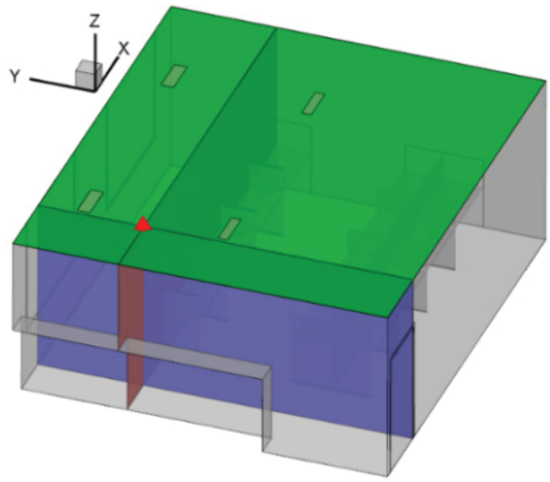

Figure 7. Optimal placement in case_17

4. Conclusions

In this paper, the monitoring of indoor formaldehyde under various conditions is studied by orthogonal experiment and CFD simulation, and the monitoring method is optimized based on genetic algorithm. The following conclusions are obtained.

1) According to the orthogonal experiment, the influence of air distribution and pollution source location on formaldehyde monitoring results should be considered first.

2) It was found that the relative position of the supply air flow and the pollution source affected the diffusion of formaldehyde in the room. Through CFD simulation, the formaldehyde concentration at each position in the room can be clearly known, so that the error of monitoring data caused by different monitoring positions and whether it needs to be corrected have a certain understanding.

3) Through further research on the genetic algorithm solution, the accurate optimal monitoring position is given. In the optimization process of 17 working conditions, 76% of the working conditions only need one sensor and correction, which can make the monitoring effective coefficient λ reach more than 80%, and 24% of the working conditions need two sensors.

By discovering and solving the problems faced by real-time monitoring of formaldehyde in practical applications, this paper can improve the monitoring effect of formaldehyde and promote the application of real-time monitoring in practice. To a certain extent, it can promote the healthy development of the industry, improve the level of indoor air quality, and protect people's physical and mental health.

The monitoring data correction method suitable for engineering practice obtained in this study needs to be further verified by more measured data. In addition, the research object of this paper is indoor formaldehyde. Although formaldehyde has certain representativeness, it still has limitations and cannot represent all indoor pollutants. In order to better realize the real-time monitoring of indoor pollutants, further research should be carried out on more types of pollutants and single parameter monitoring and multi parameter monitoring.

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