Experiment and CFD Simulation Study on Indoor PM2.5 Concentration Control in Office Buildings

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Abstract. In order to further study the law for the change of PM2.5 concentration in atmospheric environment impact on the indoor environment, projects use the experimental and CFD simulation method to quantitatively calculate the PM2.5 emission rate of cigarettes which is the main pollution sources of office building indoor. At the same time the method of experiment was used to verify the indoor PM2.5 control theory based on mass balance of indoor PM2.5 concentrations, and thus for the further study of PM2.5 and control of indoor PM2.5 concentrations provides certain scientific basis and theoretical guidance.

Keywords: CFD simulation; Experiment; Mass balance; Indoor PM2.5 Concentration.

1. Introduction

In 2013, "haze" became the annual keyword. During January 2013, there were 4 haze processes and shrouded 30 provinces(cities and autonomous regions), while in Beijing, only 5 days were not haze days. With the emergence of this large-scale "haze" phenomenon, there is another upsurge of PM2.5 research in China. The problem of air pollution caused by the continuous spread of haze weather not only gives the public a new understanding of air pollution and PM2.5, but also has gradually aroused the attention of Chinese government departments to particulate pollutant PM2.5 and the thinking of the existing extensive production mode. The diameter of PM2.5 is less than 0.05 thickness of human hair, and the Chinese name is "fine particle". Existing studies show that due to the influence of the source and formation conditions of PM2.5, the physical shapes of PM2.5 are different, including spherical, square, diamond and so on [1].

In recent years, numerous medical studies have shown that there is a clear positive correlation between the incidence rate and mortality of human beings [2]. Indoor is the main place where people live and work. People spend most of their time in it. Some studies show that [3], an ordinary person needs to inhale 255500 m3 of air in his life. So much air needs to pass through the alveoli with a total surface area of about 60 ~ 80m2 and diffuse from the alveoli to other organs. If the pollutants in the air contact with human organs for a long time, it will have an unpredictable impact on human health. The research and investigation report on indoor air quality conducted by China Association for standardization also pointed out that [4], indoor air pollutants account for 68% of the source of human diseases. Many existing research data results show that the pollution degree of PM2.5 in Urban Indoor Environment in China is relatively serious. Therefore, the research on the formation mechanism, source, and indoor concentration distribution characteristics of indoor PM2.5 has become a common concern in the research fields of public health and indoor air quality, The prevention and control of indoor PM2.5 has reached the point of urgency. Compared with the model test, which costs a lot of manpower, material resources and time, the numerical simulation method is used to study the indoor air flow distribution, analyze the influence of the purification device on the flow field, so that the air flow distribution presents a predetermined state, and realize the controllability of the air flow state, with short cycle and low cost. The simulation software FLUENT used in this paper was launched by American fluent Inc. in 1983. It is a relatively popular commercial CFD software in the world at present.

2. Measurement and analysis of indoor PM2.5 concentration

2.1. Testing and experimental devices and equipment

The PM2.5 dust tester used in the test and experiment is 8532 handheld aerosol detector produced by TSI in the United States, and its main parameters are shown in the table below:

Table 1 main technical parameters of TSI 8532 handheld aerosol detector

Project	Technical indicators
Sensor type	**90 optical dispersions**
Aerosol concentration range	**0.001-150mg/m3**
resolving power	**±0.1% reading**
Particle size range	**0.1-15μm**
Operating temperature	**0-50℃**
Operating humidity	**0-95% Relative humidity, no condensation**
data record	**5MB memory (> 60000 data points) 1 minute sampling interval can be recorded for 45 days**
Recording interval	**Adjustable, 1 second to 1 hour**
Cutting head	**1μm, 2.5μm, 4μm and 10μm4 , in total**

Table 2 main technical parameters of TEs hot wire anemometer

Project	Technical indicators
Wind speed sensing range	**0-30m/s**
Resolution	**0.01 m/s**
accuracy	**± 3% reading value ± 1% full scale**
temperature range	**-10-60℃**
Humidity range	**10-95% Relative humidity, no condensation**
Data record	**Automatic recording memory capacity 5 × 99 groups**
Recording interval	**Adjustable, once a second**

2.2. Setting of boundary conditions and simulation parameters

1. The indoor supply air volume and return air volume are stable values, which are the average values of the tested air volume.

2. The enclosure structure is set with insulation boundary.

3. PM2.5 concentration from outdoor to indoor due to infiltration and other effects and PM2.5 concentration produced by coagulation and resuspension of indoor particles are not considered.

4. The reduction rate and generation rate of PM2.5 of other indoor objects are not considered.

5. Indoor PM2.5 is evenly distributed at the initial time.

The turbulence model selected in the mathematical model is the standard K- ε Equation model.

3. Theoretical analysis and experimental design of indoor PM2.5 concentration control

3.1. Control theory of indoor PM2.5 concentration

The control theory of indoor PM2.5 concentration is based on indoor mass balance theory. The concentration of atmospheric suspended particulate matter in indoor environment depends on the rate at which outdoor particulate matter enters and leaves the room, the rate at which particulate matter is eliminated, transformed and resuspended in indoor environment, and the rate at which particulate matter is produced indoors. If the indoor generation source of particles is not considered, the change of particle concentration in the room with volume V within time t can be expressed as follows:

$$V\frac{dC_i}{dt} = [Quantity\ of\ particles\ entering\ the\ room] - \begin{bmatrix} Quantity\ of\ particulate\ matter\ in\ the\ opening \\ chamber \end{bmatrix} - [Amount\ of\ indoor\ particulate\ matter\ removed\ due\ to\ deposition, filtration, etc] + [Quantity\ of\ particulate\ matter\ emitted\ by\ indoor\ pollutant\ emission\ source]$$

Assuming that the air is isotropic, there is no temperature difference between the air and the indoor object surface, the indoor particle concentration is uniform, and the pollution source is stable, the indoor PM2.5 mass balance control equation is expressed as follows:

$$V\frac{dC}{dt} = Q_s C_s + Q_{os} C_o - Q_{is} C_i - Q_h C_i + S - R \quad (1)$$

V is the room volume (m^3); QS is the air supply volume, m^3 / s; Qh is return air volume, m^3 / s; Qis is the air volume from indoor to outdoor, m^3 / s; Qos is the air volume from outdoor to indoor, m^3 / s; Cs, Ci and Co are PM2.5 concentration of air supply and PM2.5 concentration of indoor and outdoor respectively, mg / m^3; S. R is the formation and disappearance rate of indoor PM2.5, mg / s.

3.2. Design of experimental method

Because there are many disturbances in large space and it is difficult to carry out the experiment, this paper selects a small room as a simplified small model for the experiment. The main experimental methods in this paper refer to the national standard of air purifier [5] (GB / T 18801-2015) and the performance test method of portable household electric indoor air purifier [6] (ANSI / AHAM AC-1-2006) of American household appliance manufacturers association (AHAM) and carry out a series of indoor PM2.5 concentration experiments with cigarette smoke. The experimental site is a room with a volume of 4m × 5.3m × 2.5m = 53m^3. Before the test, the wind speed of the door and window gap is tested, and its tightness is good. Therefore, the penetration of the door and window can be ignored in the next test and analysis. During the experiment, the indoor temperature is 27 ℃ and the relative humidity is 42%, meeting the experimental environment requirements of cigarette smoke experiment in air purifier (GB / T 18801-2015).

4. Experimental results and analysis

4.1. PM2.5 emission and natural attenuation of cigarette smoke

For office buildings, indoor PM2.5 pollution mainly comes from human activities, such as smoking and sweeping the floor. However, compared with other pollution sources, PM2.5 pollution caused by smoking is the most serious. Although domestic and foreign scholars have a consensus on this conclusion, there are still few experiments in China to quantitatively calculate the PM2.5 concentration emission of cigarette smoke, so the PM2.5 environment outside the office building was good on the day of the experiment, and the average outdoor PM2.5 concentration on the day was 5 μg / m3, and the PM2.5 concentration value in the laboratory is treated as 0 through the purifier μg / m3. Firstly, the PM2.5 emission of cigarette smoke was tested. Three cigarettes were lit successively in the laboratory. The combustion time was 30min, and each cigarette was burned for about 10min. The indoor concentration peak reached 517 after the cigarette was burned out μg / m3, calculated according to the volume of the room, the total emission of three cigarettes is 27.401mg/m3, and the PM2.5 emission of each cigarette is very uniform, that is, the PM2.5 emission concentration of each cigarette is 9.134mg/cigarette. In the second test, three cigarettes were lit at the same time. After burning for 10 minutes, the PM2.5 peak in the house reached 500 μg / m3, that is, the PM2.5 emission concentration

of each cigarette is 8.833 mg / cigarette, which is not different from the first experiment. The PM2.5 emission of cigarettes measured in the above experiment is after deducting the natural attenuation. Therefore, to accurately obtain the PM2.5 emission of cigarettes, the natural attenuation experiment is carried out.

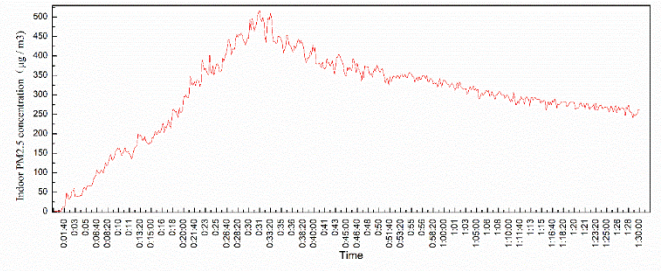


Fig. 1. Variation of indoor PM2.5 concentration during experiment 1

The natural attenuation time is 1H, i.e. 60min. Figure 1 show that the PM2.5 concentration in t Indoor PM2.5 concentration he laboratory shows a linear downward trend after reaching the peak. According to the national standard of air purifier (GB / T 18801-2015) and the performance test method of portable household electric indoor air purifier (ANSI / AHAM AC-1-2006) of American household appliance manufacturers association (AHAM) The calculation method of natural attenuation constant in is as follows:

$$C_t = C_0 e^{-kt} \tag{2}$$

Where Cti is the PM2.5 concentration at time t(μg / m^3), C_0 is the PM2.5 concentration at the initial time(μg / m^3), K is the natural attenuation constant, t time unit is min. Take logarithms on both sides of the above formula, and the formula (4-2) is as follows:

$$ln\, C_t = \ln C_0 - kt \tag{3}$$

Take the logarithm of indoor PM2.5 concentration value for linear regression, and its slope value is the PM2.5 natural attenuation constant of cigarette smoke. The linear regression diagram is shown in Figure 2.

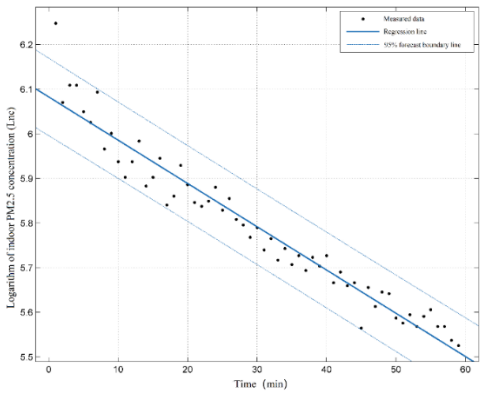


Figure 2. Linear diagram of natural attenuation of cigarette smoke

The R^2 of the natural attenuation linear diagram obtained in the experiment is 0.9413, although it is slightly lower than the requirement that R^2 is greater than 0.98 in the national standard of air purifier (GB / T 18801-2015) and the performance test method of portable household electric indoor air purifier (ANSI / AHAM AC-1-2006) of American household appliance Manufacturers Association (AHAM), However, because the test time in this experiment is much longer and more points are taken than its standard test method, the results are basically reliable and the linear relationship is good. The natural attenuation constant of PM2.5 is 0.009698 min^{-1}.

According to the literature, the calculation formula of indoor pollutant source concentration emission is as follows:

$$\frac{dC_{\text{in}}}{dt} = P\alpha C_{\text{out}} + \frac{Q_S}{V} - (\alpha + \kappa)C_{in} \quad (4)$$

Where CIN is the indoor PM2.5 concentration (μg / m^3), cout is the outdoor PM2.5 concentration (μg / m^3), P is the penetration efficiency, the number of indoor air changes, the generation rate of indoor pollution source, K is the natural attenuation rate, and V is the laboratory volume (m^3). By deforming formula (4-3), the following formula can be obtained:

$$\bar{Q}_S = V \times \left[\frac{C_{int} - C_{in0}}{\Delta T} + \overline{(\alpha + \kappa)} \times \overline{C_{in}} - \alpha \times C_{in0}\right] \quad (5)$$

Where $\bar{Q}_S$ average generation rate of indoor pollution source, C_{int} Int is the concentration of indoor PM2.5 t (μg /m3), C_{in0} is the concentration of indoor PM2.5 at the initial time(μ g/m3), $\overline{(\alpha + \kappa)}$ Is the average removal rate, ΔT is the time interval. According to the above formula and the data measured in Experiment 1, it can be calculated that the PM2.5 production of each cigarette used in the test is 11.79mg/cigarette and the production rate is 1.179mg/min. According to the research of literature C. he et al [7], the emission concentration of PM2.5 of cigarette smoke is 0.99mg/min, o. zkaynak et al. [8] The study shows that the emission concentration of PM2.5 of cigarette smoke is 13.8 ± 3.6mg/cigarette, which is not different from the research results of this paper, indicating the reliability of the research results of this paper.

4.2. PM2.5 purification experiment of cigarette smoke

In the purification experiment, the experimental environment is good, and the indoor and outdoor PM2.5 concentration is stable at 0 μg / m^3, so it can be considered that there is no outdoor PM2.5 infiltration. For better experimental comparison, a cigarette was lit before the experiment to stabilize the indoor PM2.5 concentration at 124 μg / m^3, i.e. the initial concentration in the room is 124 μg / m^3, then light the cigarette, keep the indoor cigarette burning for 1 hour, turn on the purifier at the same time, place two TSI-8532 handheld aerosol detectors at the inlet and outlet of the purifier respectively, set them to record data every 30 seconds, and the recording results are shown in Figure 3.

It can be seen from Figure 3 that although the inlet and outlet concentration values of the purifier are small and fluctuate greatly at the initial stage of the experiment, the inlet and outlet concentration values of the purifier are relatively stable after a few minutes of cigarette combustion, in which the outlet concentration is basically stable at 100 μg / m^3, while the inlet concentration is basically stable at 220 μg / m^3, the PM2.5 concentration in the room is basically stable.

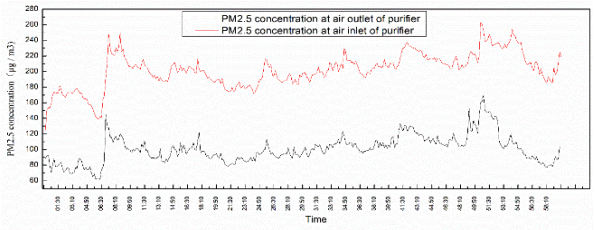


Fig. 3 variation diagram of inlet and outlet concentration of purifier in purification experiment 1

To better compare the theoretical value with the experimental value, figure 4 is as follows. As can be seen from Fig. 4, the data actually tested in the experiment are quite consistent with the data predicted by the balance theory, which shows the reliability of the theory.

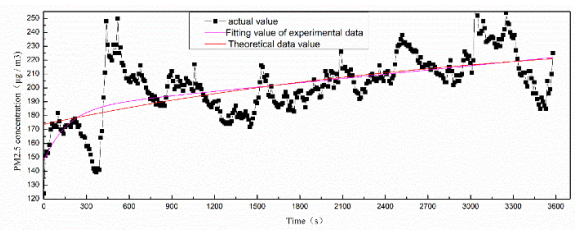


Fig. 4 comparison and change of indoor concentration between actual value and prediction in purification experiment.

4.3. CFD simulation results

Figure 5 shows the particle distribution on the typical cross section (x=2.15m) of the room where the PM2.5 source is located in the initial state. On the whole, the concentration distribution of PM2.5 particles in most indoor spaces is relatively uniform, and the concentration difference is large only at the source.

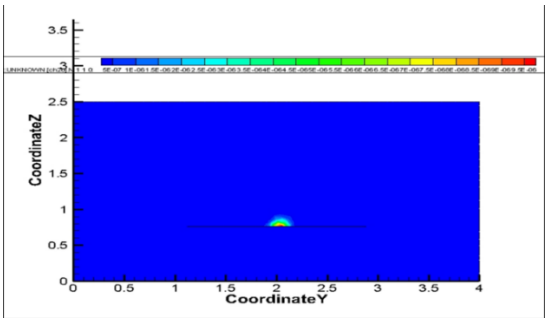


Fig. 5 Cloud map of PM2.5 concentration distribution in the experimental room (initial state)

The dimensionless concentration distribution of indoor PM2.5 when the indoor PM2.5 concentration reaches equilibrium for a period of time during the experiment is shown in Figure 5 and Figure 6. It can be seen from the figure that on the interface of plane x=2.5, the concentration of PM2.5 near the purifier is low during equilibrium, and the concentration of PM2.5 increases along the Y-axis and z-axis. From the perspective of concentration value, the dimensionless concentration value of PM2.5 in the room simulated by FLUENT is slightly smaller than the value measured in the test.

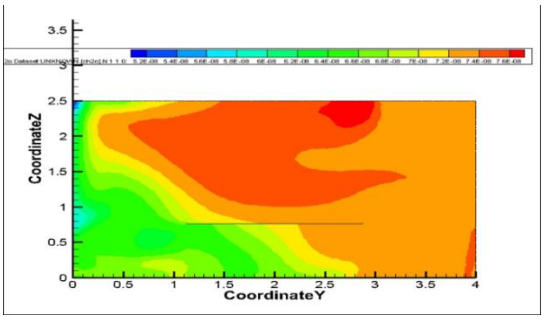


Fig. 6 Cloud map of PM2.5 concentration distribution in the experimental room (x=2.5)

On the interface of plane y=2, the concentration distribution in the room is more uniform than that on the interface of plane x=2.5, because the interface of x=2.5 is close to the purifier, and the air flow disturbance is large, while the interface of y=2 is located in the center of the room, and the disturbance by the air flow of the purifier is small. At the same time, it can be found that the dimensionless concentration of PM2.5 on the interface with y=2 is much higher than that on the interface with x=2.5. This is because the interface with y=2 is close to the source of PM2.5, that is, cigarettes, and the purifier is far away, so this phenomenon is caused.

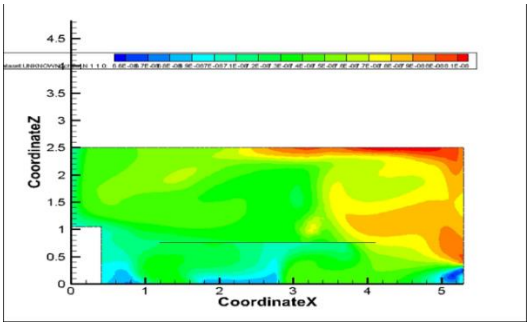


Fig. 7 Cloud diagram of PM2.5 concentration distribution in the experimental room (y=2)

5. Conclusions

According to the experiment, the natural attenuation constant of PM2.5 particles in cigarette smoke (for ordinary cigarettes), the main indoor PM2.5 pollution source, is 0.009698min-1, the emission is 11.79mg/min, and the emission rate is 1.179mg/min.

For the indoor household purifier, its efficiency is not as high as its nominal value, and the efficiency fluctuation is obvious. In addition, the indoor PM2.5 concentration control theory based on indoor mass balance theory can accurately predict the change of indoor PM2.5 concentration under certain conditions, which provides a certain scientific basis and theoretical guidance for the further study of PM2.5 and PM2.5 concentration in the control room.

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