Performance evaluation and improvement of local exhaust systems in a pharmaceutical workshop

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Abstract

In pharmaceutical workshops, harmful pollutants produced during the production process could be dispersed in the indoor environment. The emission of those pollutants is an important factor threatening the health of workers and of other occupants. In this paper, we studied pollutant emission characteristics to evaluate the quality of indoor air (IAQ) in one pharmaceutical workshop. It would release a large amount of particulate pollutants during the opening process of the centrifugal equipment because of the existing external suction hood ventilation system in the workshop during the production of the magnesium isoglycyrrhizinate injection material. We found that the particle size distribution had a peak for particles with optical particle size between 0.3 μm and 1 μm. The measured data also shows that the centrifugal equipment also released a large amount of volatile organic compounds (VOCs). To reduce the exposure concentration for workers, we propose an improved ventilation strategy, with an annular air curtain near the centrifugal equipment to create a pull-push ventilation strategy. We performed a three-dimensional numerical simulation of the flow field and of the pollutant concentration in transient conditions. We found an increased exhaust performance with the improved ventilation strategy, compared with the exhaust hood only. In fact, the capture efficiency of particulate pollutants increased by installing the annular air curtain.

Keywords: Local hood ventilation system; CFD; particulate pollutants; VOC

1. Introduction

In industrial ventilation, to prevent the harmful pollutants generated in the production process from polluting the air of the workshop, we need to collect the harmful pollutants on the spot through the exhaust hood and deliver them to the purification equipment for treatment by exhaust duct. Afterwards, they are recycled or discharged into the atmosphere after they meet the requirement of the discharge concentration set by the law.

Both the general ventilation and the local ventilation strategies have been used in industrial application. One kind of the local ventilation strategies, *i.e.*, the push-pull ventilation system, proved to be efficient in controlling indoor harmful pollutants. Under the same conditions, the push-pull ventilation device can save 50% of the airflow when compared with the local exhaust hood (such as the side exhaust hood) (Malin,1945). During the design process of ventilation strategy, we need to consider the influence of the non-uniform heat density of the factory environment on the ventilation efficiency. Both the flow rates of the exhaust hoods and the source strength are important factors for the efficiency of pollutant capture (Huang *et.al*. 2015). In the horizontal push-pull ventilation system, designers give the relevant design values for push and pull hoods in ACGIH manual (1995). Yang *et al*. (2019) found that the ventilation performance of the horizontal push-pull ventilation (PPV) was superior to that of the upper receiving ventilation (URV) system. He *et al.* (2000) proposed a combined scheme of the exhaust hood assisted by a jet. By using the computational fluid dynamics, they established the mathematical model of the flow field, and obtained the air distribution of the push-pull ventilation system. Some studies also reported the application of air curtain in the kitchen ventilation system (Zhou *et. al*. 2016）.

In this paper, we investigated the pollutant emission characteristics in a pharmaceutical workshop. We propose an improved ventilation strategy, which includes the exhaust hood ventilation system and the annular air curtain. We report the results on the performance of the original and improved ventilation strategies obtained by computational fluid dynamics (CFD) three-dimensional simulations in transient conditions.

2. Materials and methods

2.1 Experiment and methods

We performed the measurement in a pharmaceutical workshop located in Lianyungang, China. The workshop produced the magnesium isoglycyrrhizinate injection material. The size of the plant was 18 m (L) x 9 m (W) x 6 m (H). There were many centrifuges inside the workshop. Due to the large size of the workshop, we selected the typical position to measure the distribution of airborne pollutants.

We connected the Agilent data acquisition logger with type K nickel-chromium-silicon thermocouples to obtain the temperature values in the measuring area. We used hot wire anemometry and PMS5003 particulate matter concentration sensor to measure the exhaust velocity and Concentrations of PM_1, $PM_{2.5}$, and PM_{10} respectively. CLJ-3016L was used to measure the particle number concentration. The size ranges of the instrument were 0.3−0.5 μm, 0.5−1 μm, 1−3 μm, 3−5 μm, 5−10 μm, and >10 μm. In addition we measured the concentration of VOCs in the workshop by PGM-7340. We made the measurements at four different locations, A1 (-1, 0.2, 1.4), A2 (0, 0.35, -0.6), A3 (0, 0, 1.8) and A4 (-1.15, 1.52, 0.8). We recorded the data every minute. We carried out three times of sampling at each sampling position. The measurement process lasted 50 minutes. Fig.1 shows the positions of the measuring points, and Table 1 shows that the whole process can be divided into three stages. We measured the concentration of pollutants and the diffusion of pollutants during the opening and closing processes of the centrifuge.

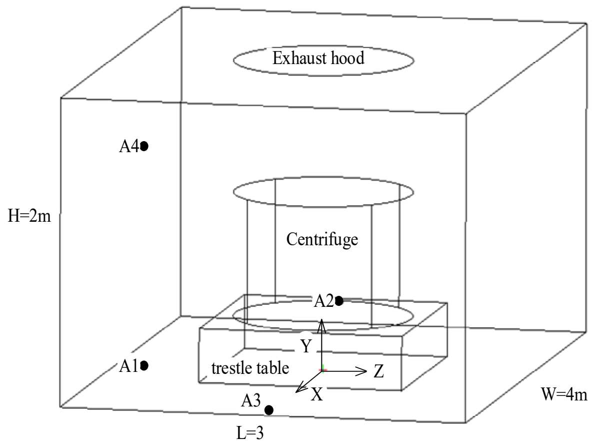


Fig. 1 Measurement positions in workshop

Table 1 Three stages in experiment

	Stage1	Stage2	Stage3
Exhaust hood	+	+	+
Centrifuge	-	+	-

+:Operating conditions of the machine

-: Non-operating conditions of the machine

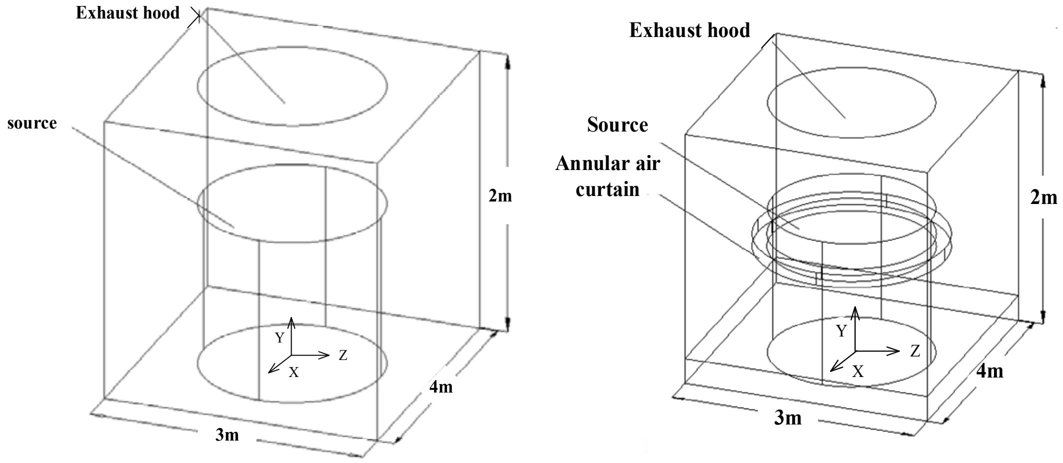
2.2 Numerical simulation

2.2.1 Physical model

In good agreement with the layout of the pharmaceutical workshop, as well as with the size and the location of the centrifugal equipment, Fig. 2 and Fig. 3 show the corresponding physical models and the geometry of the exhaust hood and push-pull ventilation system respectively. Table 2 shows the detailed parameters of the exhaust hood and of the push-pull ventilation system. We measured the indoor environment parameters during a hot summer period: the ambient temperature of the plant was 32±0.3°C. The average of the multiple measurement data was taken as the input value for the boundary condition for the CFD simulation. To facilitate the preparation of the model and its meshing, we simplified the model as follows.

The objective of this study was the pollutant diffusion of a centrifuge, so we established the physical model of one centrifuge to simplify the calculation. We defined the center point of the centrifugal equipment as the coordinate origin.

The fluid was incompressible. It was an isothermal environment due to no significant change in temperature profile during the measurement process.



a. Model of exhaust hood b. Model of push-pull ventilation system

Fig.2. Illustration of the original and improved ventilation models

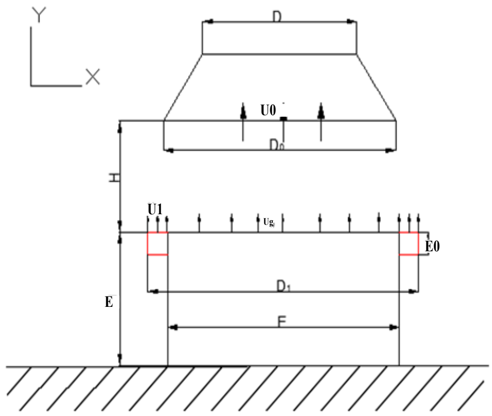


Fig.3. Geometry of models

Table 2. Parameters of exhaust hood and push-pull ventilation system

Exhaust hood		Push-pull ventilation system	
Parameter	Value	Parameter	Value
F(m)	1.30	F(m)	1.30
D(m)	0.20	D(m)	0.20
D_0(m)	1.30	D_0(m)	1.30
u_0(m/s)	1.50	D_1(m)	1.50
u_g(m/s)	0.03	u_0(m/s)	1.27
		E_0(m)	0.20
		u_g(m/s)	0.03
		u_1(m/s)	0.63

2.2.2 Mathematical model

The governing equations solved include three-dimensional incompressible Navier-Stokes equations, the energy equations, the continuity equation, as well as the turbulence equations. Zhang *et.al* (2007) gave the specific coefficients and source terms for Eq. (1).

$$\rho\frac{\partial\bar{\emptyset}}{\partial t}+\rho\bar{u_j}\frac{\partial\bar{\emptyset}}{\partial X_j}-\frac{\partial}{\partial X_j}\left[\Gamma_{\emptyset,eff}\frac{\partial\bar{\emptyset}}{\partial X_j}\right]=S_{\emptyset} \tag{1}$$

where $\emptyset$ represents variables, $\Gamma_{\emptyset,eff}$ is the effective diffusion coefficient, and $S_{\emptyset}$ is the source term of an equation.

Using the Lagrangian discrete random walk model, we simulated airborne particle movement to predict the trajectory of the discrete phase by integrating the equilibrium equation of the forces acting on the particles. Eq. (2) included the force balance involving particle inertia, gravity, drag, and Brownian forces.

$$\frac{d\vec{u}_p}{dt} = F_D(\vec{u}_a - \vec{u}_p) + \frac{\vec{g}(\rho_p - \rho_a)}{\rho_p} + \vec{F}_a \quad (2)$$

where $F_D(\vec{u}_a - \vec{u}_p)$ is the drag of the particles per the unit mass; $\vec{u}_a$ is the fluid phase velocity and $\vec{u}_p$ is the particle velocity; ρ_a and ρ_p is the air and particle density; $\vec{g}$ is the gravitational acceleration; $\vec{F}_a$ is the additional forces, besides gravitation, thermophoretic force and Saffman lift.

He *et.al* (2002) believed that the simulated data with the standard κ-ε model was closer to the experimental value, whose consistency was better than that with RNG κ-ε model. This paper used the standard k-ε turbulence model. We applied the second-order upwind momentum and SIMPLE algorithm. Then we generated the mesh of models by GAMBIT 2.4. Fig.4 shows the velocity in the y-axis direction with distance from the exhaust hood when we refined the cells gradually. Finally, we used 5540758 cells, since it showed the best compromise between resolution accuracy and computing time.

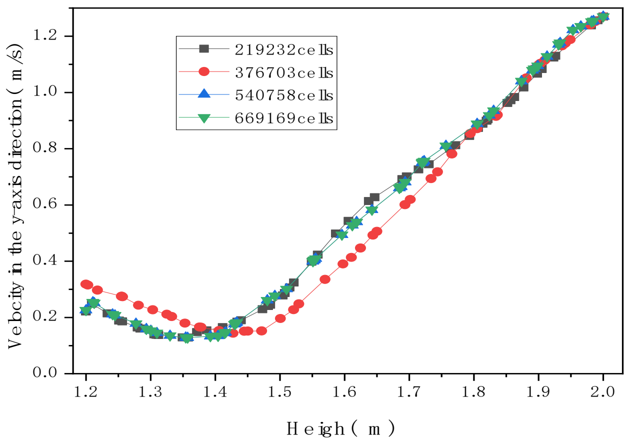


Fig.4. Velocity in the y-axis direction with distance from the exhaust hood with four grid cell numbers

3. Results and discussion

Fig. 5 shows the number concentration for different size bins at the measurement points. The most frequent particle contaminant size was 0.3-1 µm in the indoor environment of the pharmaceutical workshop. Its concentration was about 50 times higher than that of the particles with 1-10 µm size range. Fig. 6 shows the concentration of PM_1 at the measurement points. The PM_1 concentration at the A2 and A3 positions fluctuated greatly. Because these points were closer to the centrifuge and particulate pollutants were diffused. The particle concentration at the A2 and A3 positions was higher during the stage 2 (operation of centrifuge and exhaust hood ventilation system). The concentration of A1 was lower than that of A3. The reason for this phenomenon is the deposition of particulate pollutants.

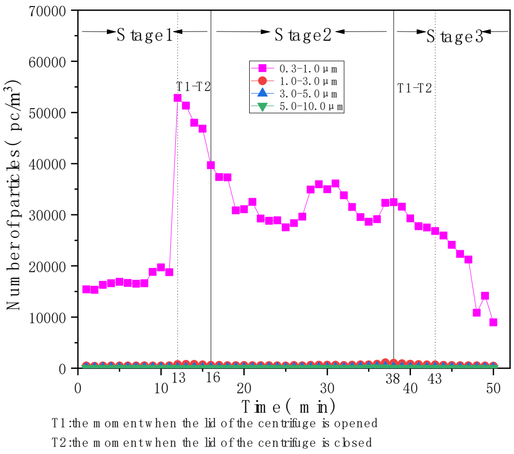


Fig.5. Particle number concentration vs. time

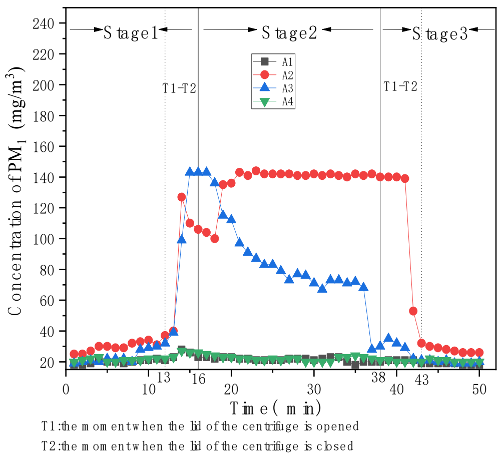
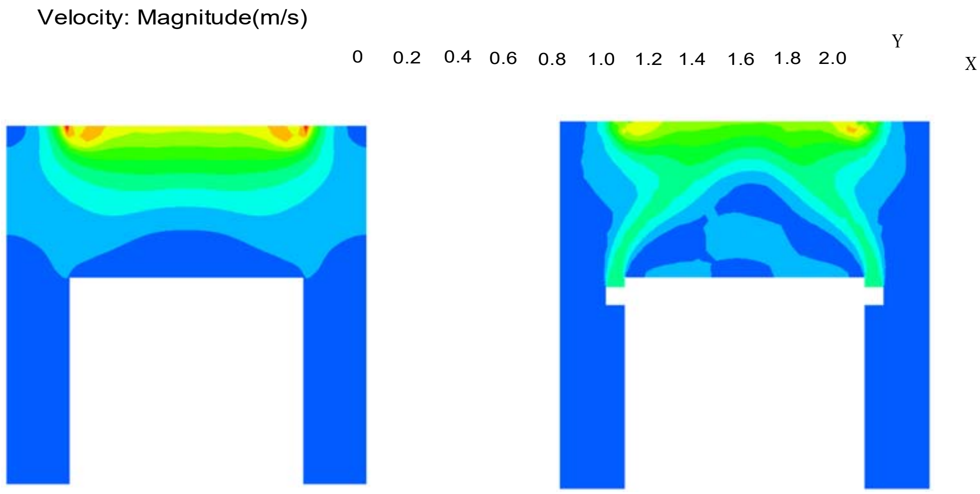


Fig.6. Concentration of PM_1 in experimental site vs. time

Combined with Fig. 5 and Fig. 6, the concentration of particulate contaminants is lower in exhaust hood during the stage1 and stage3 processes. However, in the processes of T1-T2, the contaminants suddenly fluctuated. This was possibly due to the release of the residual particulate matter remaining in the centrifuge shell during the opening process of the lid. When centrifuge stopped the operation and closed the lid of the centrifuge, the pollutants greatly descended. The experiment also found a large amount of VOCs contaminants throughout the test environment. The concentration of VOCs was 89 ppm when all the centrifugal equipment was inactive. However, the maximum concentration of VOCs in the local working area reached 8464 ppm in the running state of centrifuge equipment, which seriously affects the working environment.

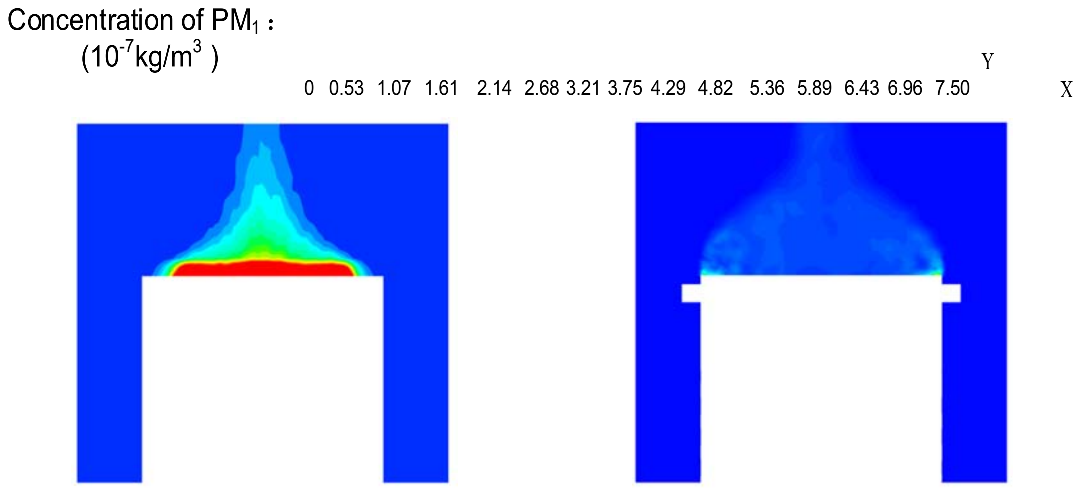
As shown in Fig. 7(a), due to the influence of airflow characteristics, the airflow velocity decayed quickly with the distance after being ejected from the hood. In this case, the flow field became slow near the centrifuge. Comparing Fig. 7(a), the disturbance range to the surrounding air was smaller in the push-pull ventilation system, and the exhaust air velocity was smaller in Fig. 7(b). To some extent, it blocked the influence of transverse airflow, improved the collection efficiency and prevented the spread of pollutants.

Fig. 8 shows the concentration of PM_1 with the exhaust hood and the push-pull ventilation strategy. In the exhaust hood ventilation, contaminants accumulated around the source of pollution, and the concentration was higher. The airflow in the exhaust hood did not carry most of the contaminants in Fig. 8(a). In the case of the push-pull ventilation system, the particle concentrations in the flow field were below 35 μg/m^3. If the exhaust airflow rate is the same, the capture efficiency of the push-pull ventilation system is higher. Fig. 8(b) shows that the exhaust airflow can be appropriately reduced, and the exhaust air exhausting requirements are met, so that the ventilation system consumes less electric energy.



a. exhaust hood b. push-pull ventilation system

Fig.7. Velocity field with simple exhaust hood and push-pull ventilation system



a. exhaust hood b. exhaust hood with air curtain

Fig.8. The concentration of PM_1 in exhaust hood and push-pull ventilation system

4. Conclusions

This paper studies the diffusion of pollutants in a pharmaceutical workshop, with two different local ventilation systems. The pharmaceutical workshop contained a large number of particulate contaminants. The particle size distribution had a peak for particles with optical particle size between 0.3-1 μm, and its concentration was about 50 times that of the particles with diameter 1-10 μm. Meanwhile, it would release large amounts of volatile organic compounds (VOCs). The centrifuge leaked contaminants during operation and affected the working environment inside the workshop.

The numerical simulation shows that the improved system can enhance the exhaust performance compared with the exhaust hood only. After installing the annular air curtain, the capture efficiency of the particulate pollutants was improved. To some extent, it blocked the influence of transverse airflow, improved the collection efficiency and prevented the spread of pollutants, which improves the quality of indoor air in pharmaceutical workshops.

Acknowledgement

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References

American Conference of Governmental Industrial Hygienists (ACGIH), (1995) Industrial ventilation, a manual of recommended practice, *MI: ACGIH*

Huang Y, Wang Y, Liu L, *et al.* (2015) Reduced-scale experimental investigation on ventilation performance of a local exhaust hood in an industrial plant, *Building and Environment*, **85**: 94-103

He YS, Wang YM, Su T. (2000) Parameter optimisation of a push-pull exhaust hood, *Journal of HV&AC*, **30**（**5**）:9-11 (In Chinese).

He SY, Wang YM, Li YF. (2002) Flow-field test and simulation of a three-dimensional Aaberg exhaust hood, *Journal of Shanghai Jiaotong University* , **36(10)**:1492-1495

Malin B S. (1945) Practical pointers on industrial exhaust system. *Heat＆Ven*, **42**:75−78

Yang Y, Wang Y, Song B, *et al.* (2019) Transport and control of droplets: A comparison between two types of local ventilation airflows, *Powder Technology,* **345**:247-259

Zhou B, Chen F, Dong Z, *et al.* (2016) Study on pollution control in residential kitchen based on the push-pull ventilation system, *Building and Environment,* **107**:99-112

Zhang, Z., Zhang, W. (2007) Evaluation of Various Turbulence Models in Predicting Airflow and Turbulence in Enclosed Environments by CFD: Part-2: Comparison with Experimental Data from Literature, HVAC & R Research **13(6)**, 871-886.