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Research on simulation and optimization of light density gas based on replenished air hood

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Abstract
In this paper, a multi-mode replenishment type exhaust cabinet is designed to remove pollutants of different densities in the cabinet by changing the position and Angle of replenishment and the position of exhaust air. In this paper, the performance of the light density model in the treatment of pollutants such as hydrogen is analyzed by numerical simulation, and the influence of the exhaust system and air distribution of the exhaust cabinet on the pollutant removal effect is evaluated. The research shows that the optimal design of light density mode can reduce the leakage rate of exhaust cabinet and improve the performance and efficiency of exhaust cabinet. In light density mode, the upper side and bottom exhaust vents are used to exhaust air. When the air supply Angle is perpendicular to the exhaust vents, the exhaust cabinet has higher safety. A downward air curtain is set at the lower end of the operating cabinet door to better control the leakage of pollutants.

Keywords: *Supplementary air type exhaust cabinet, Light density pollutants, Numerical simulation, Energy conservation.*

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I. INTRODUCTION

Exhaust cabinet is an important ventilation equipment in scientific research laboratory, and its exhaust efficiency directly affects the concentration of pollutants in the laboratory and the safety of laboratory staff.

Exhaust cabinets have a very wide range of applications in engineering. According to the JB/T 6412-1999 exhaust cabinet standard [1], when the standard ejector discharge SF6(sulfur hexafluoride gas) at a flow rate of 4L/min, the concentration on the operating surface should be less than 0.5ml/m^3.

Supplementary air exhaust cabinet is a common improved exhaust cabinet. The primary air volume inhaled from the operating surface is reduced by air replenishment in the cabinet. Jia Chunxing et al. [2] proposed to set the air supplement function column on the outer back of the cabinet to send fresh air into the cabinet from the operating port to effectively reduce the gas turbulence in the cabinet. Wang Chuping et al. [3] proposed to bring fresh air along the air duct on both sides of the cabinet to the inner side of the operating port in the cabinet to generate oblique blowing air with an Angle of 15°-75°, carrying pollutant gas to the exhaust outlet to reduce leakage.

The computational fluid dynamics simulation of the exhaust cabinet by Omar et al. [4] found that the recirculation area behind the window sash was a potential factor leading to the leakage of pollutants, and the openings on the baffle would reduce the recirculation area, thereby reducing the backflow that might lead to leakage. Meng et al. [5] studied the influence of different baffle opening and air supply speed of supplementary air exhaust cabinet on blowdown performance, and the optimal air supply speed was 0.45m/s, 0.5m/s and 0.55m/s.

However, the physical properties of pollutants are different, which will greatly affect the diffusion of pollutants.Zhuang Xiaodong et al. [6] studied the effects of carbon dioxide release speed and release temperature on the diffusion process under static wind conditions. Li Xi, Guo Yong et al. [7] studied the influence of leakage holes of different positions and sizes on heavy gas diffusion in typical rooms. By simulating three exhaust cabinets, Zhang Yong [8] concluded that the bottom exhaust cabinet is suitable for the emission of large specific gravity gas.

To sum up, the research on the heavy density pollutants in the exhaust cabinet has already existed to study the corresponding better ventilation mode. However, light density pollutants are more difficult to control than heavy density pollutants, so it is very meaningful to study the optimization of air flow organization of multi-mode exhaust cabinets for light density pollutants.

In this paper, a multi-mode replenishment type exhaust cabinet is designed to adapt to the removal of light density pollutants in the cabinet by changing the position and Angle of the replenishment air and the position of the exhaust air. And through the experiment combined with CFD simulation research method, the operation mode of exhaust cabinet for light density gas is obtained.

II. RESEARCH METHOD

In this paper, CFD simulation method is used to study and optimize to control the leakage of pollutants. In order to verify the accuracy of CFD simulation method, experiments were carried out in a self-built environment chamber.

2.1 CFD validity verification experiment

The geometric parameters of the environment chamber for CFD simulation results used for verification are shown in Figure 1.

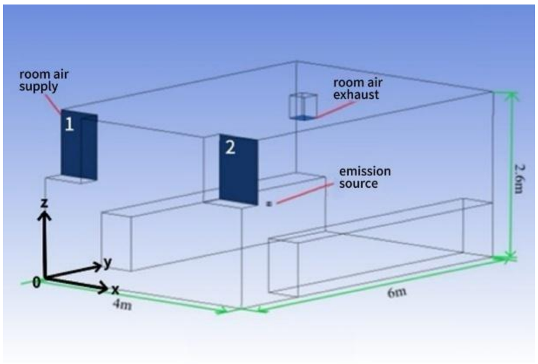


Figure 1:Physical dimensions of the environmental chamber

The air flow organization studied in this paper is lower supply air and upper exhaust air. The two air supply ports are placed on the left and right sides of the environmental room, with a length of 0.6m, a width of 0.3m and a height of 2.4m. The fan selected for this verification experiment is 30Hz, and the corresponding air speed of the air supply port is 0.67m/s and 1.06m/s.

In this paper, SF6 was used as a tracer gas to test its diffusion distribution in an environmental chamber. The emission source of SF6 is placed in the central position with a height of 1.0m and the height of the measuring point is 1.5m.

2.2 Verify the CFD simulation results of the experiment

The CFD simulation of the verification experiment adopted a 1:1 model, and the software Fluent meshing was selected in this paper to generate unstructured tetrahedral mesh. The work of local mesh encryption was carried out at the outlet, the source and the wall, and the total mesh number was 4.04 million. The resulting grid is shown in Figure 2, and the encrypted portion is shown in Figure .

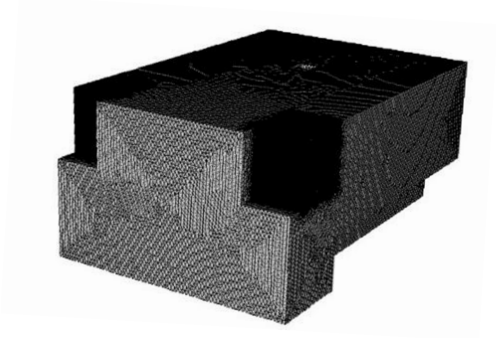


Figure 2: Grid division diagram

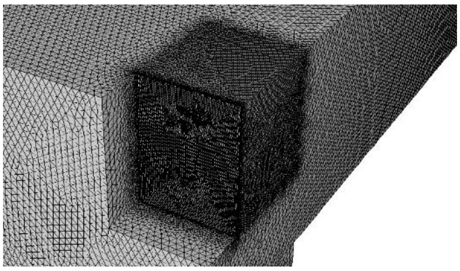
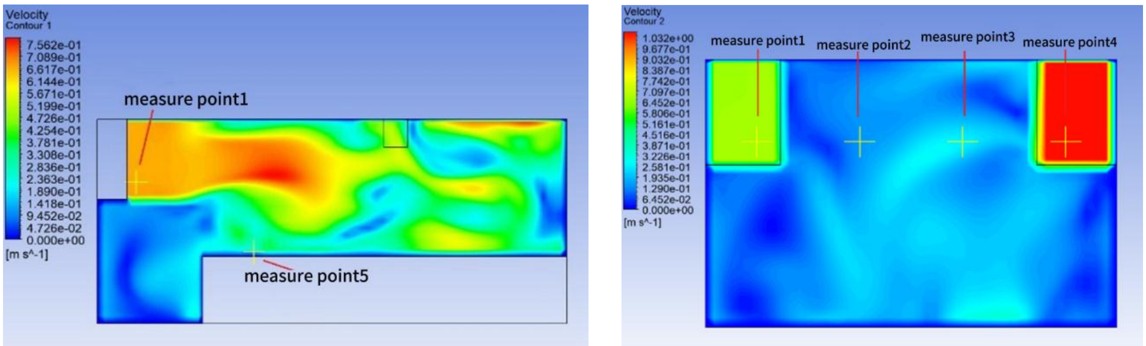


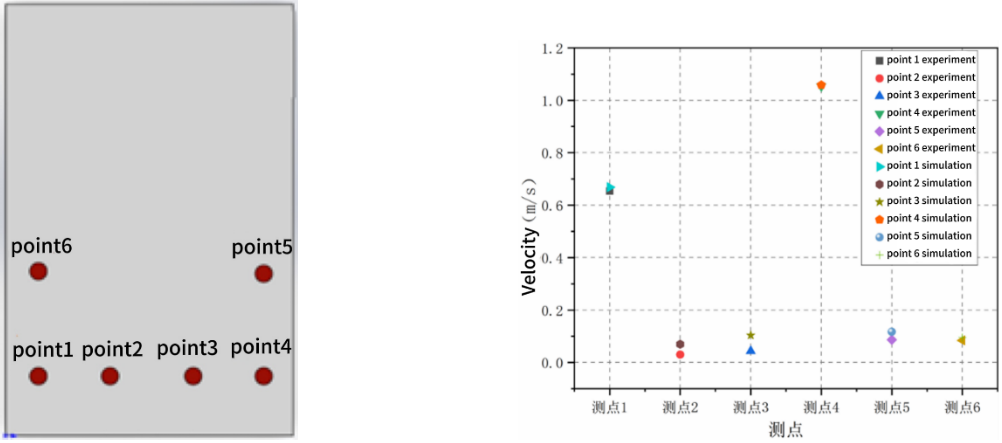
Figure 3: Local magnification diagram of air supply port grid

The boundary conditions set in this paper are consistent with those in the experiment. The outlet is a pressure outlet. The dispersion source is based on the SF_6 flow during the experiment.

The steady-state simulation is selected, and the component transport model is selected considering the influence of gravity. The standard k-e model was adopted for turbulence model [9], and the standard wall function was adopted for near-wall processing. The governing equations are obtained by using the solution method of SIMPLEC and the second-order upwind scheme. The convergence conditions of numerical simulation are as follows: 1) continuity residual is less than 1×10-3; 2). Energy residual less than 1×10-6; 3). Calculate that the traffic balance within the domain is less than 1%.



(a) Velocity cloud image with X=0.5m **(b) Velocity cloud image with Y=0.5m**

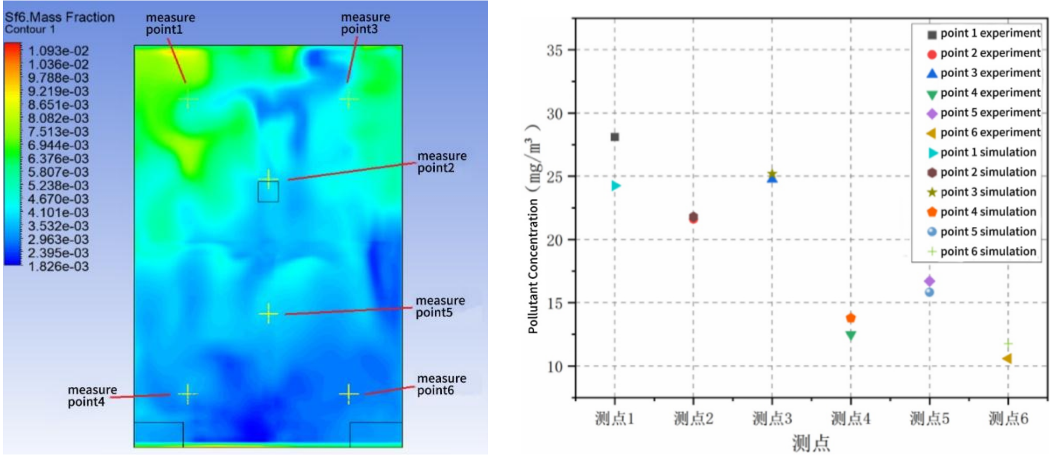


(c) Flow field measuring point layout **(d) Flow field measurement point data diagram**

Figure 4: Location map, velocity cloud map and data comparison map

As can be seen from Figure 4d, the wind speed at measuring points 1 and 4 near the air supply outlet is relatively high, while the wind speed at several measuring points far away from the air supply outlet is relatively low. The experimental and simulated data are basically consistent.

For the data of pollutant concentration field, the results are shown in Figure 5.



(a) Cloud map of pollutant concentration with Z=1.5m **(b) Pollutant concentration field data diagram**

Figure 5: Concentration field measuring point data diagram

As can be seen from Figure. 7b, the pollutant concentration at measuring points 4 and 6 near the air supply outlet is low, the pollutant concentration at measuring points 5 near the emission source is high, and the pollutant concentration at measuring points 4, 5 and 6 far away from the emission source is slightly higher than that at measuring points 4, 5 and 6. Due to the high air volume at air supply outlet 2, the pollutant concentration at measuring point 1 is higher than that at measuring point 3, and the consistency between experimental and simulation results is good.

The concentration and relative error of pollutants obtained from the experiment and simulation are summarized in Table 1 below:

Table 1: Experimental and numerical simulation data sheet

Station position	Experimental pollutant concentration (mg/m³)	Simulated pollutant concentration (mg/m³)	δ_f
Measure Point 1	28.10	24.26	13.67%
Measure Point 2	21.61	21.79	-0.83%
Measure Point 3	24.77	25.19	-1.70%
Measure Point 4	12.49	13.79	-10.41%
Measure Point 5	16.70	15.83	5.21%
Measure Point 6	10.59	11.74	-10.86%

As can be seen from Table 1, the relative error range of experimental pollutant concentration and simulated pollutant concentration is -10.86% ~ 13.67%, the minimum relative error is -0.83%, and the average relative error value is -0.82%. The location of measurement point 1 is far from the location of air supply outlet, and the test fluctuation is large, so there is a certain error.

From the simulation results, the mesh generation method, turbulence model and component transport model used in CFD simulation are suitable for this study.

2.3 Multi-mode supplementary air exhaust cabinet

The multi-mode supplementary air type exhaust cabinet designed in this paper has a light gas mode designed for the emission of light density pollutants, so as to improve the airflow organization in the exhaust cabinet and reduce the leakage of pollutants. Its structure is shown in Figure 6. Five air supply air outlets are set in the air supply section, namely inlet1-5. The size of inlet1-3 is 1.34m x 0.05m, that of inlet4 is 1.4m x 0.015m, and that of inlet5 is 1.4m x 0.025m. There are five exhaust positions in the exhaust department, namely outlet1-5. The size of outlet1-4 is 1.34m x 0.1m, and the size of outlet5 is 1.34m x 0.15m. Figure 7a below shows the Settings of the air supply and exhaust vents in the exhaust cabinet.

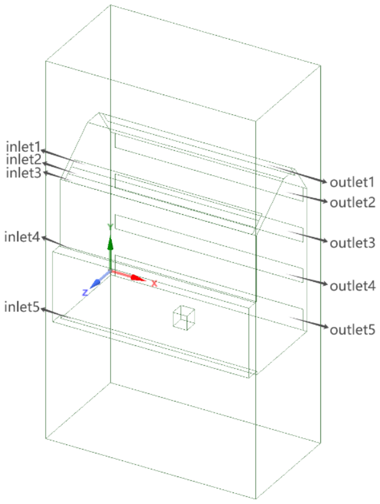
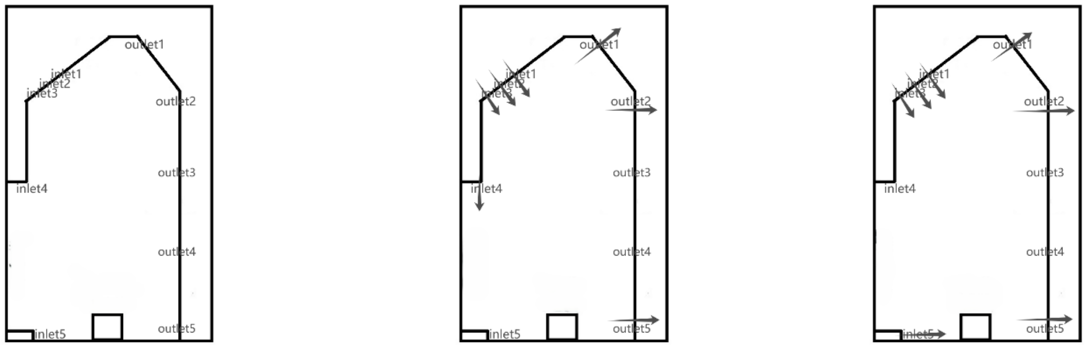


Figure 6: Simplified diagram of multi-mode exhaust cabinet model

This paper sets the following two modes for the light gas mode, namely, the air curtain replenishment mode as shown in Figure. 7b and the strip sewing replenishment mode as shown in Figure. 7c. For the exhaust mode of light density pollutants, hydrogen is used as the tracer pollutant, the air supply Angle is perpendicular to the tuyair, open the air curtain of the upper air supply port inlet1-3 and the air curtain of the air supplement inlet4, open the upper air supply port inlet1-3 and the slit type of the operating port of the lower side of the air supplement inlet5. The exhaust vents are outlet1, outlet2 on the upper side of the diversion exhaust panel, and outlet5 on the lower side.

After a series of simulations, we can get a screenshot of the emission concentration cloud map of light density pollutants with hydrogen as an example.



(a) Multi-mode supplementary air exhaust cabinet

(b) Air curtain supplementary air mode

(c) strip supplementary air mode

Figure 7: Schematic diagram of air supply and exhaust in the exhaust cabinet

2.4 Simulation model and working condition

The simulation model established in this paper is shown in Figure 8. The size of the laboratory is 5.0 meters long, 5.0 meters wide and 3.0 meters high, and the exhaust cabinet is located in the middle of the laboratory near the wall. The laboratory is provided with two air supply ports at the pressure inlet on the top of the laboratory. The size of each air supply port is 0.6 m ×0.6 m. The xyz axis coordinate system is established at 0 point in the upper left corner of the operating surface of the exhaust cabinet.

Referring to ANSI/ASHRAE 110-2016 standard [10], five concentration monitoring points are set up in this paper where the breathing zone is 22 inches (550 mm) above the operating table and 3 inches (75 mm) beyond the cabinet door. Three parallel planes were selected based on this plane, when Z= 0.875m, 0.8m and 0.7m respectively, and the average pollutant concentration of each plane was measured as the optimization index.

In order to better compare the two ventilation modes, the paper adopts the combination of different air supply outlets, air supply angles and exhaust outlets to carry out simulation calculations for a total of 6 working conditions. The detailed working conditions are shown in Table 2.

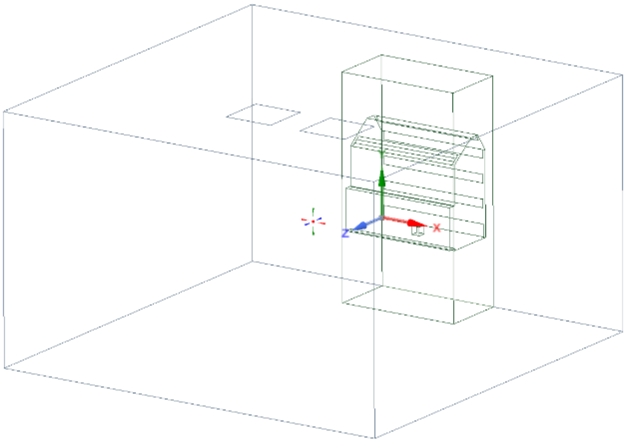


Figure 8: Schematic diagram of air supply and exhaust in the exhaust cabinet

Table 2: Simulated condition

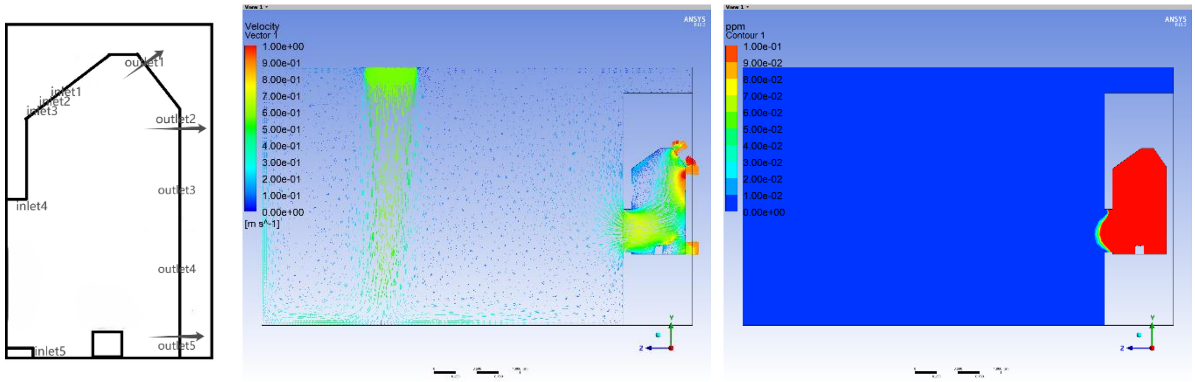
Working condition	Setting	Outlet	Exhaust air volume (m^3/h)	Inlet	Supplementary air volume (m^3/h)	Supplementary air Angle	Tracer gas	Tracer gas emission rate (L/min)
1	Standard mode	1、2、5	1500	/	/	/	hydrogen	4
2	Air curtain replenishment air mode	1、2、5	1500	1、2、3、4	750	Perpendicular to the tuyere	hydrogen	4
3	Strip sewing pattern	1、2、5	1500	1、2、3、5	750	Perpendicular to the tuyere	hydrogen	4
4	Adjust the air supply Angle	1、2、5	1500	1、2、3、4	750	Straight down	hydrogen	4
5	Adjust the air supply Angle	1、2、5	1500	1、2、3、5	750	Straight down	hydrogen	4

6	Locally adjust the air supply Angle of the strip seam	1、2、5	1500	1、2、3、5	750	Straight down	hydrogen	4

III. RESEARCH RESULT

3.1 Standard mode

The simulation model established in this paper is shown in Figure 9. The size of the laboratory is 5.0 meters long, 5.0 meters wide and 3.0 meters high, and the exhaust cabinet is located in the middle of the laboratory near the wall. The laboratory is provided with two air supply ports at the pressure inlet on the top of the laboratory. The size of each air supply port is 0.6 m ×0.6 m. The xyz axis coordinate system is established at 0 point in the upper left corner of the operating surface of the exhaust cabinet. For the light density gas mode, the main goal is to improve the efficiency and safety of the exhaust cabinet in removing pollutants with low density and easy upward diffusion. Use supplementary air to form displacement air flow and avoid causing the diffusion of pollutants. Working condition 1 is the standard exhaust cabinet mode.



(a)Schematic diagram of air supply and exhaust in working condition 1

(b)Velocity vector diagram of X=0.75m under working condition 1

(c)H2 pollution emission diagram of X=0.75m under working condition 1

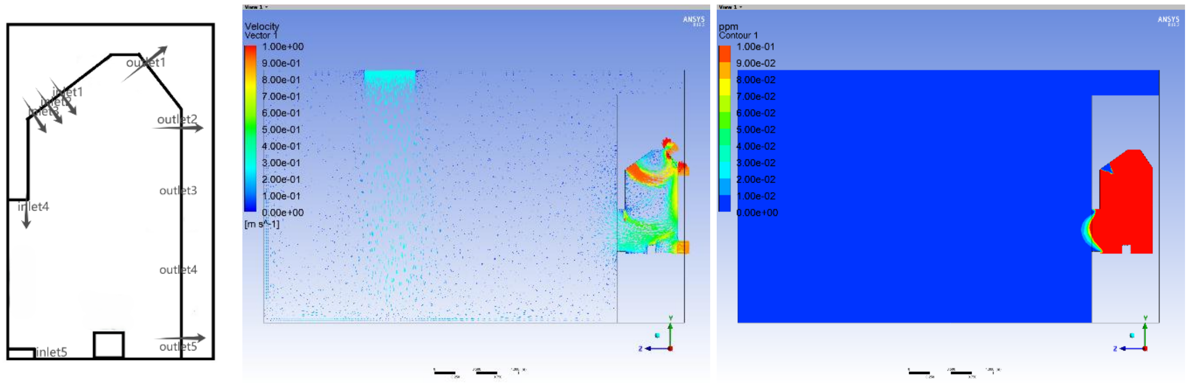
Figure 9: Simulation results of working condition 1

It can be seen from the experimental results that under the standard mode, the emission of light density pollutants represented by hydrogen can be controlled to a certain extent, but its diffusion trend still exists, especially near the cabinet door, a small amount of light density pollutants diffuse outward. This phenomenon is mainly due to the physical characteristics of light density pollutants. Compared with heavy density pollutants, light density pollutants have smaller molecular mass and faster diffusion rate, so it is more difficult to control light density pollutants under the same control conditions.

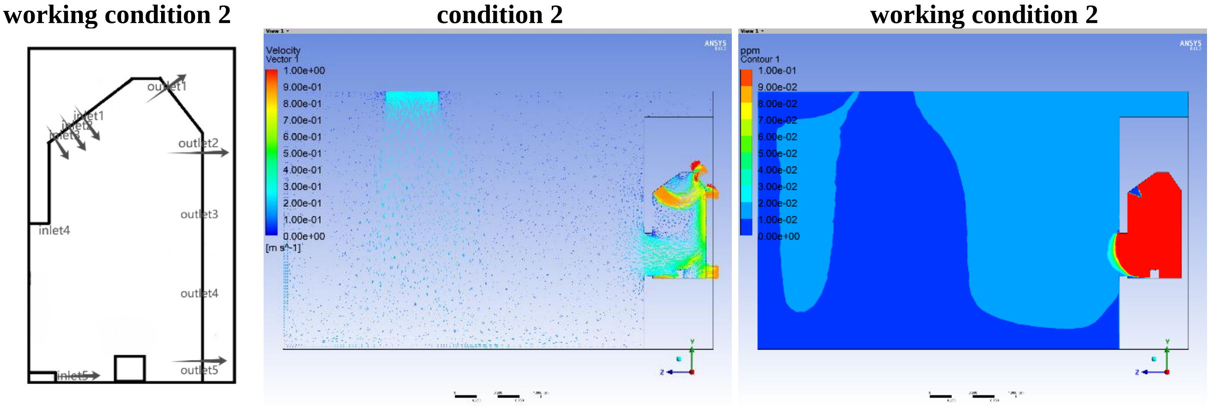
3.2 Add air curtain or strip repair air optimization

For light density pollutants due to the role of buoyancy, the exhaust air on the upper part of the exhaust cabinet has a better effect.However, relying solely on exhaust air can increase the energy consumption of the system, especially if a high exhaust speed needs to be maintained. Therefore, while ensuring the effect of pollutant control, reducing energy consumption has become an important optimization direction.

In order to take into account pollutant control and energy consumption efficiency, the design of air curtain and strip sewing air can be considered in the exhaust cabinet. Therefore, the optimization of light density mode is mainly carried out by changing the Angle and type of air supplement based on the light density mode designed in this paper. It is designed to control and eliminate pollutants with lower density more effectively, reduce the risk of leakage, and improve the overall performance and safety of the exhaust cabinet. Condition 2 is the air curtain replenishment mode. Working condition 3 is strip mending air mode.



(a)Schematic diagram of air supply and exhaust in working condition 2 **(b)Velocity vector diagram of X=0.75m under working condition 2** **(c)H2 pollution emission diagram of X=0.75m under working condition 2**



(d)Schematic diagram of air supply and exhaust in working condition 3 **(e)Velocity vector diagram of X=0.75m under working condition 3** **(f)H2 pollution emission diagram of X=0.75m under working condition 3**

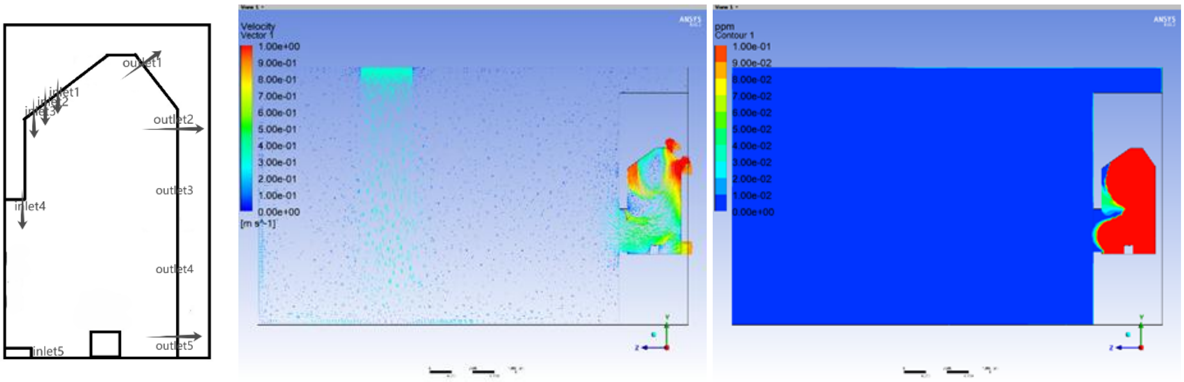
Figure 10: Simulation results of working condition 2&3

It can be seen from the results of working condition 2 that although the air supply outlet plays a role in drainage, there are still pollutants leakage and local accumulation at the operation port. This indicates that the diffusion of pollutants has been reduced to a certain extent, but the control effect is still not ideal. Compared with condition 1, the total amount of pollutants is reduced, but the leakage problem cannot be completely solved, especially near the operation port, the concentration of pollutants is still high.

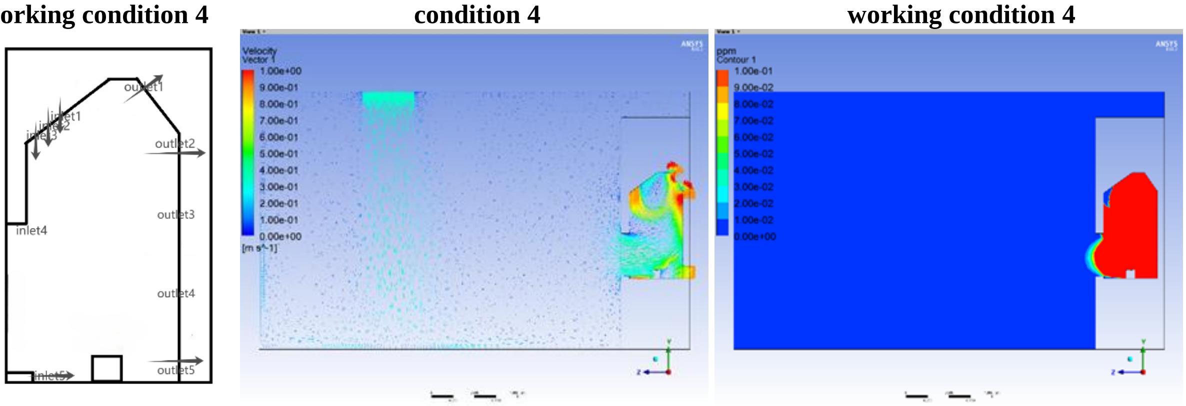
When the strip sewing air was added (condition 3), the results unexpectedly showed that the leakage of pollutants not only did not improve, but increased. The vertical downward airflow introduced by the strip repair air and the airflow that naturally rises due to buoyancy form a confluence of airflow in the middle area of the exhaust cabinet, resulting in the retention of pollutants here, forming a "retention layer". The presence of this retention layer prevents pollutants from being effectively discharged, but instead accumulates in the cabinet, ultimately exacerbating the leak.

3.3 Adjust the upper air supply Angle to optimize

For light density pollutants such as hydrogen, due to its small molecular mass, fast diffusion speed and significant buoyancy effect, the traditional Angle of air supply perpendicular to the tuyere may not be able to completely control its diffusion, which is easy to lead to leakage. This is because although the Angle of compensating air perpendicular to the tuyere can form an air flow barrier to a certain extent, due to the buoyancy of hydrogen, it is still easy to escape upward, especially in the case of incomplete matching between the compensating air flow and the diffusion direction of pollutants. Therefore, in order to control the diffusion of hydrogen more effectively, it is a more reasonable optimization scheme to adjust the Angle of recharging air to vertical down. Working condition 4 is the air curtain replenishment mode of adjusting the upper replenishment Angle. Working condition 5 is the strip mending air mode which adjusts the Angle of upper mending air.



(a)Schematic diagram of air supply and exhaust in working condition 4 **(b)Velocity vector diagram of X=0.75m under working condition 4** **(c)H2 pollution emission diagram of X=0.75m under working condition 4**



(d)Schematic diagram of air supply and exhaust in working condition 5 **(e)Velocity vector diagram of X=0.75m under working condition 5** **(f)H2 pollution emission diagram of X=0.75m under working condition 5**

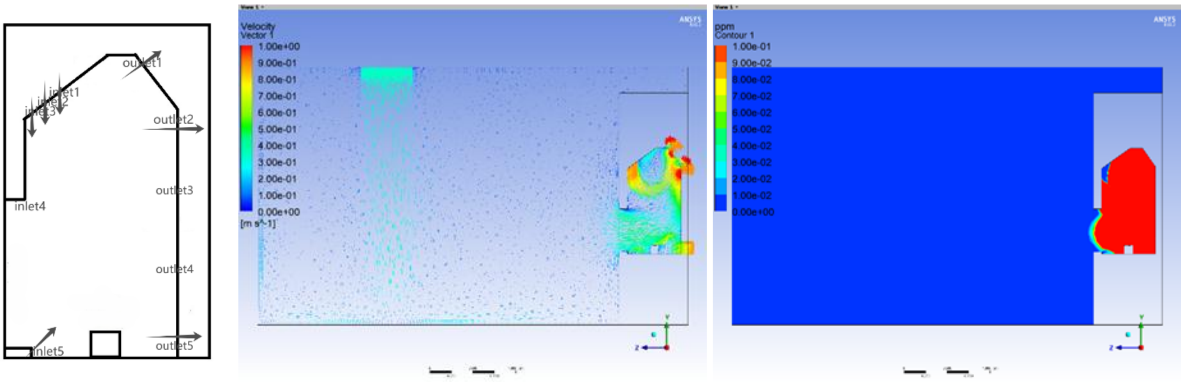
Figure 11: Simulation results of working condition 4&5

From the point of view of working condition 4, the vertical downward replenishment air and the air curtain replenishment air drive the flow of pollutants to the exhaust air outlet, bringing good results, and the pollution at the operation port is significantly reduced. It can be seen from the experimental results of working condition 4 that the design of vertical downward air supplement combined with air curtain significantly improves the control effect of pollutants, and the concentration of pollutants at the operating port is significantly reduced.

As shown in Figure 11f (working condition 5), the pollutant leakage is significantly reduced compared with Figure 10f (working condition 3), which indicates that the vertical downward supplementary air design has a significant effect on the emission control of light density gases (such as hydrogen). However, a small amount of pollutants still accumulate at the operation port.

3.4 Adjust strip stitching to optimize air Angle

Through the above research, it is found that simply changing the air supply Angle of the upper air supply outlet can not significantly improve the air flow organization and pollutant emission effect in the exhaust cabinet. Therefore, this paper tries to optimize by adjusting the air supply Angle of the seam. Working condition 6 is the strip sewing air repair mode that adjusts the upper air supply Angle and the strip seam air supply Angle.



(a)Schematic diagram of air supply and exhaust in working condition 6

(b)Velocity vector diagram of X=0.75m under working condition 6

(c)H2 pollution emission diagram of X=0.75m under working condition 6

Figure 12: Simulation results of working condition 6

Compared with conditions 5 and 6, it can be seen that the pollutant leakage at the operation port is significantly reduced after the strip sewing air repair mode with oblique upward air replenishment is adopted. This improvement is mainly due to the optimal design of the oblique upward air supply Angle, which makes it more suitable for the diffusion characteristics of light density pollutants such as hydrogen. An oblique upward air supply Angle (e.g. 45°) can better direct contaminants to the outlet while reducing their accumulation near the operating port. Compared with the air supply Angle perpendicular to the tuyere, the oblique upward air supply can more effectively cover the operating port area, especially when the cabinet door is opened or closed, which can significantly reduce the instantaneous leakage of pollutants.

Table 3: Pollutant concentration on the selected surface of working condition 1-6

Working condition	Average concentration on one side of plane (ppm)	Average concentration on two sides of plane (ppm)	Average concentration on three sides of plane (ppm)
1	9.02E-03	9.03E-02	2.96E+02
2	1.08E-02	5.69E-02	1.79E+03
3	2.44E-02	2.06E-01	5.90E+02
4	2.54E-03	1.10E-02	1.55E-01
5	7.41E-03	3.51E-02	1.63E+00
6	6.33E-04	1.30E-02	1.13E+00

Table 3 summarizes the comparison of the results of different working conditions when the pollutant is light density gas. It can be seen that operating conditions 4 and 6 have the lowest risk of exposure to pollutants.

IV. CONCLUSION

By means of experimental verification and CFD simulation, this paper studies the discharge performance of multi-mode replenishment type exhaust cabinet for light density pollutants, and optimizes air flow organization for light density mode. Conclusions are as follows:

(1) The multi-mode supplementary air exhaust cabinet designed in this paper has better pollutant removal effect than the supplementary air exhaust cabinet. Compared with the ordinary type exhaust cabinet, the primary air exhaust volume can be reduced by 50% with the same effect, saving air conditioning energy consumption, and it has more advantages in pollutant removal capacity compared with the ordinary supplementary air exhaust cabinet.

(2) Changing the air supply Angle in light density mode is conducive to improving the removal efficiency, and the air supply Angle perpendicular to the air supply outlet has the highest efficiency. Compared with the heavy air mode, the concentration of light density pollutants is more difficult to control, and there is little room for optimization through the Angle of air supplement.

(3) Because the air outlet of the light density mode is far away from the pollutants, the light density gas diffuses faster. Therefore, a downward air curtain is set at the lower end of the operating cabinet door to better control the leakage of pollutants.

REFERENCES

[1]. JB/T 6412-1999, exhaust cabinet [S].

[2]. Chunxing Jia, Replenishment type exhaust Cabinet, 201811157263.8 [P],2019-02-01.

[3]. Chuping Wang, A New type of Internal replenished air exhaust cabinet, 202010160509.8[P],2021-03-16.

[4]. Omar M A A, Wisnoe W, Bakri A. Effect of Baffle Opening Position to the Flow Distribution in a Servco Fume Cupboard[C]//Applied Mechanics and Materials. Trans Tech Publications Ltd, 2014, 465: 566-570.

[5]. Meng C, Liu D, Gao N, Li L. Investigation on improving fume hood performance via elimination of internal vortices: Experiments and CFD[J]. Indoor and Built Environment. 2022; 31 (10) : 2467-2481.

[6]. Chaoneng Zhang, Ping Ning, Caixia Ma. Analysis of influencing factors of heavy gas leakage and diffusion [J]. Journal of Wuhan University of Technology,2010,32(05):97-100.
[7]. Xi Li, Yong Guo, Xiaoqi Jin, Linlin Zhu, Guili Yang, Zongqun Li. Simulation of argon leakage in enterprise Workshop [J]. Journal of Suihua Institute,20,40(12):154-157.
[8]. Lijun Wei. Numerical simulation of heavy gas diffusion process [D]. Beijing: Beijing University of Chemical Technology,2000.
[9]. Olazo-Gomez Y, Xaman J, Gijon-Rivera M, et al. Mathematical modelling of conjugate laminar and turbulent heat transfer in a cavity: Effect of a vertical glazed wall[J]. International Journal of Thermal Sciences, 2020, 152: 106310.
[10]. ANSI/ASHRAE Standard 110-2016: Methods of Testing Performance of Laboratory Fume Hoods. ASHRAE: Atlanta, 2016.