# Numerical simulation of pollutant diffusion in public toilets

*Xin* Yin[1], *Xinshan* Sun[1], *Minkai* Bai[1], and *Zhan* Liu[1*]

1 School of Mechanic and Civil Engineering, China University of Mining and Technology, Xuzhou, China

**Abstract.** Compared with residential restrooms, public toilets usually have higher utilization rates. How to ensure the air quality in the toilets through reasonable ventilation is of great significance to human health. In this study, an office building with a public toilet is selected as the research object, and the Airpak 3.0 software is adopted to simulate the airflow velocity distribution in the toilet with different air change rates and exhaust vent heights. Variations of the air velocity distribution, ammonia concentration, ventilation efficiency, and other parameters, are compared and analyzed. The results show that increasing the air change rate could reduce the concentration of pollutants in the toilet, but it has negative effects on ventilation efficiency. After comprehensive analysis, the desirable air change rate is chosen with the value of $15h^{-1}$. The exhaust outlet is set near the source of pollution to facilitate the discharge of pollutants. This work may provide a theoretical basis for amelioration of the toilet ventilation environment.

## 1 Introduction

Indoor air pollution is harmful to human health and has direct influences on people's daily life [1]. In public buildings, the toilet is the main source of pollutants and releases many harmful gases such as ammonia and hydrogen sulfide[2]. Ammonia can irritate and corrode human's upper respiratory tract. If someone inhales ammonia, the basic physical signs are cough, dizziness, nausea, and other symptoms. Once it is inhaled severely, the pulmonary edema or breathing difficulty may appear [3]. According to the Chinese national standard (hygiene standard for public toilets in Chinese cities, GB/T 17217–2021), the maximum concentration of ammonia in public toilets should be $<0.3$ mg/m$^3$. To satisfy the standard requirements, it is critical to quickly remove contaminants and deliver sufficient amount of fresh air[4].

Different influence factors, such as the location of air supply and exhaust outlets, the amount of ventilation, and the arrangement of indoor pollution sources, on the toilet ventilation performance, were considered and investigated. Tung et al. [5, 6] evaluated effects of the negative pressure difference, air change per hour(ACH), and the toilet location on the distribution of odor concentration in bathroom. Tung et al.[7] developed an experimental model to study the odor dispersion in toilets and concluded that indoor pollutant concentrations are lowest by using ventilation with forced air supply from the top and exhaust from the side walls. Chung et al.[8] compared the influence of window configurations on the distribution of the pollutants in a public toilet. The results show that to improve ventilation efficiency, the number of shading windows and installation locations should be properly designed. Lin et al.[9] studied the influence of architectural design parameters on the airflow patterns and acetic acid distribution in toilets. The results show that it is difficult to sustain adequate natural ventilation rates and allowable levels of harmful contamination through building design, and additional mechanical ventilation is required.

In this paper, the forced ventilation driven by the exhaust air, and air supply through the doorway are adopted to study the pollutant diffusion in public toilets. Effects of different ACHs and exhaust locations are explored on the ventilation efficiency and ammonia distribution in public toilets. Indoor air quality is evaluated by studying variations of the mean age of air(MAA), air exchange efficiency(AEE), and ventilation efficiency.

## 2 Methods

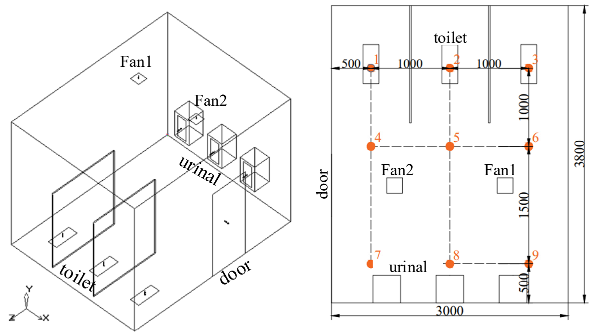
### 2.1 Numerical Model

In this study, the Fluent Airpak3.0 software is used to simulate the airflow and contaminant distribution in the public toilet, with the RNG k-ε model.

The dimension of the selected public toilet is 3.8m×3m×3m (L×W×H), with a volume of 34.8m³. Pollution sources include three toilets and three urinals. The dimension of the urinals is 0.35m×0.35m×0.6m (L×W×H). The established geometric model is shown in Fig.1a. Pollution released from the urinal and toilet is simplified to 0.5m×0.2m equivalent air inlet, with the ammonia release rate of 0.05 m/s and release concentration of $8\times10^{-7}$ kg/m³. The door is designed as a pressure outlet. Two exhaust outlets are located at the ceiling, with the size of 0.2×0.2m, and treated as constant velocity outlets. The speed of the exhaust outlet is determined by the air exchange volume calculated by the air change rate method.

* Corresponding author: liuzhanzkd@cumt.edu.cn

 https://doi.org/10.1051/e3sconf/202235605047




(a) Geometrical model (b) Location of measurement points

**Fig. 1.** Geometrical model and Schematic layout of measurement points.

### 2.2 Mesh sensitivity

In this paper, the geometric model of the toilet is divided with the structured grid. The grid independence analysis is conducted with five different meshes. One monitor is set in the toilet with the coordinates of (X=1.5m, Y=1.9m), and the simulation results are shown in Fig. 2. It is easy to see that when the grid number increases from 850,000 to 970,000, the variation of ammonia mass fraction with height is almost the same, and the root-mean-square error of speed is 0.06%. Therefore, the grid number of 850,000 is selected for our study.

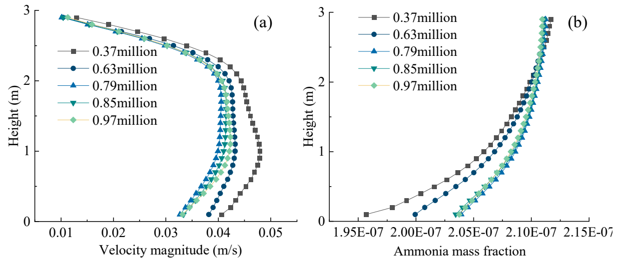



**Fig.2.** Grid-independent verification. (a) Airflow rate; (b) ammonia mass fraction.

### 2.3 Studied cases

Table 1 lists 8 parametric variations.

**Table 1.** Studied cases.

| Case | ACH | Exhausts height/m | Fan1 | Fan2 |
|---|---|---|---|---|
| 1 | 5 | 3 | on | on |
| 2 | 10 | 3 | on | on |
| 3 | 15 | 3 | on | on |
| 4 | 20 | 3 | on | on |
| 5 | 15 | 0.3 | on | on |
| 6 | 15 | 0.6 | on | on |
| 7 | 15 | 0.9 | on | on |
| 8 | 15 | 1.2 | on | on |

### 2.4 Evaluation index

As Fig.1b shows, 9 data points are evenly set in the public toilet. The simulation results of the pollutant concentration at 0.1 ~ 2.9 m are extracted from monitors the interval of 0.1 m.

The age of air refers to the time taken by air molecules from entering the room to reaching a certain point in the room[10]. The air exchange efficiency (AEE) is defined as the ratio of the shortest retention time of air to the actual whole room average retention time, which is used to evaluate the superiority of air exchange[11].

$$\mathrm{AEE} = \frac{\tau_n}{2\overline{\tau_r}} \times 100\% \tag{1}$$

Where, $\tau_n$ and $\overline{\tau_r}$ are the nominal time constant, and the MAA, respectively.

Ventilation effectiveness is an indicator of pollutant removal ability, and also known as contaminant removal effectiveness. [12].

$$\varepsilon = \frac{C_e - C_s}{C - C_s} \tag{2}$$

Where, $C_e$, $C_s$, and $C$ are the average mass fraction of pollutants at the exhaust outlet, air inlet (here $C_s$ is 0), and the entire toilet.

## 3 Results and Discussion

### 3.1 Airflow velocity distribution

The airflow velocity distribution is significant to people's thermal comfort in breathing zone. Fig. 3 demonstrates the velocity distribution of Y=0.9m under different ACHs (5, 10, 15, and 20). It is easy to see that the air from the doorway is mixed with indoor air and discharged from the exhaust outlet at the ceiling, and the airflow velocity below the exhaust vent is larger. However, there are partitions in the toilets, resulting in a small air velocity in the compartment. ACH has obvious influences on the toilet ventilation efficiency. As the ACH increases, the inlet wind speed through the doorway increases from 0.02 m/s to 0.1 m/s, and the wind speed near the urinal also increases. The increase of the air inlet speed is conducive to the pollutants dilution in the toilet, and is beneficial to improving the overall ventilation effect of the bathroom. The airflow velocity values of 4 cases are all below 0.3 m/s, and it will not cause a significant sense of blowing wind.

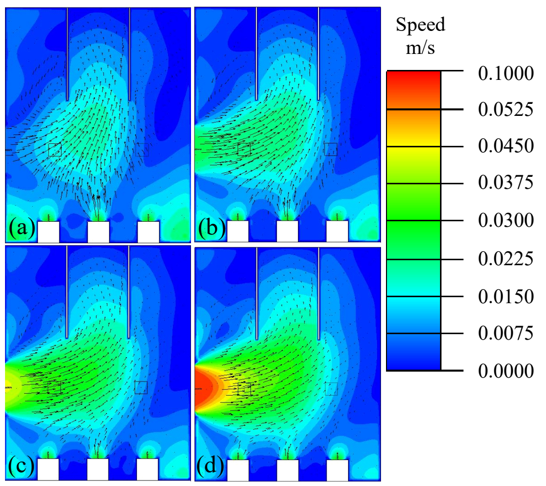



**Fig. 3.** Velocity distribution under different air change rates on Y =0.9 m plane: (a)Case1; (b)Case2; (c)Case3; (d)Case4.

Generally, increasing ACH usually causes the increase of the indoor airflow velocity and energy consumption, hence the ACH should be chosen properly. Here, the indoor airflow distribution with the air change rate of 15$h^{-1}$ is investigated under different vent heights (0.3m, 0.6m, 0.9m, 1.2m).

The air vents are placed in the toilet to extract air from the surrounding area and increase the airflow rate. As the air vents are close to the source of pollution, it is beneficial to the removal of harmful gases in the toilet. The urinals are far away from the vent, and the air disturbance around them is not obvious. The exhaust vent height change does not affect the velocity distribution in the breathing zone plane Y=0.9 m, as shown in Fig.4

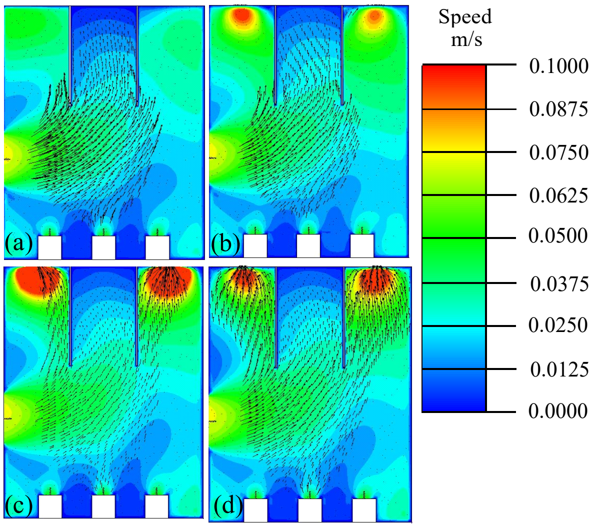



**Fig. 4.** Velocity distribution under different vent heights on Y=0.9m plane: (a)Case5; (b)Case6; (c)case7; (d)case8.

### 3.2 Ammonia concentration distribution

The ACH has significant effects on the distribution of ammonia concentration. As Fig.5 shows, when the exhaust air volume is large, the ammonia concentration on Y=0.9m plane in the breathing zone reduces obviously. Due to the arrangement of the exhaust vents, the ammonia concentration near the doorway and the exhaust outlets is lower. The ammonia concentration in the toilet is high owing to the presence of partitions. When the ACH is 5, the ammonia mass fraction is about $4\times10^{-7}$, which is much larger than the specified $2.49\times10^{-7}$. When the ACH increased to 10, the ammonia mass fraction reduces about 50%, when compared with the former, and the concentration near the pollution source is still too high. While the ACH increases from 15 to 20, the difference in dilution effect of the exhaust vent is not obvious, so the proper value of ACH is 15.

Fig.6 presents the distribution of ammonia concentration on Y=0.9m plane at different vent locations with ACH of 15. The ammonia concentration in the toilet is not uniformly distributed, and the ammonia concentration is higher in the urinals and the second toilet compartment. The ammonia concentration in the farthest toilet cubicle from the building entrance is the highest when the height of the vent is 1.2m. While the ammonia concentration in the toilet cubicle with the vent is lower when the vent height is 0.3m, 0.6m and 0.9m, and the ammonia concentration increases with height.

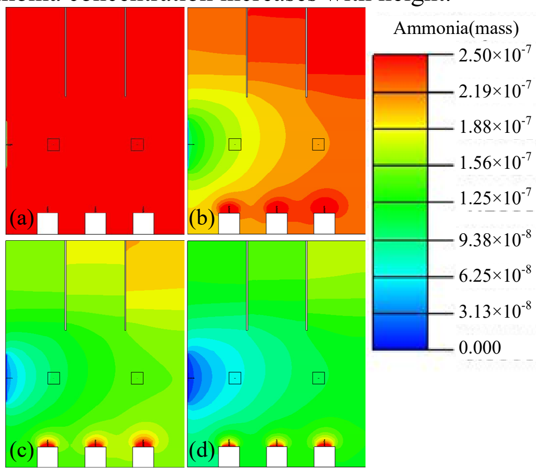



**Fig.5.** Ammonia concentration distribution under different air change rates on Y=0.9m plane: (a)Case1; (b)Case2; (c)case3 (d)case4.

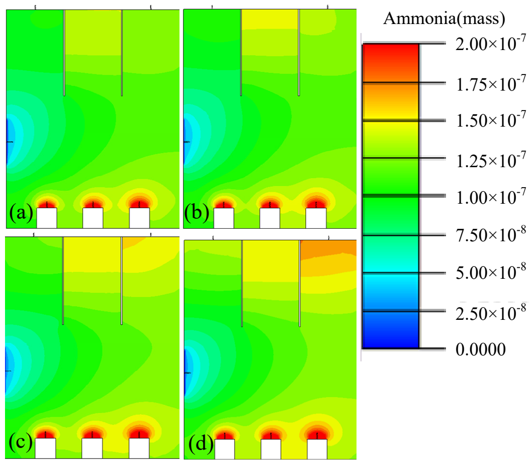



**Fig. 6.** Ammonia concentration distribution under different vent heights on Y=0.9m plane: (a)Case5; (b)Case6; (c)Case7 (d)Case8.

The vertical distribution of ammonia concentration under different vent positions, as shown in Fig.7. L1, L2, L3, and L6 are the measurement lines in the area between the toilet cubicles. Ammonia concentration in L1 reaches the maximum at 0.1 m, and the concentration first decreases and then increases with the increase of height. The airflow entering from the doorway diffuses to L1, which results in the ammonia concentration in L1 reaching a minimum at 1.1m. The ammonia concentration in L2 does not affected by the locations of the vent because there is no vent in the second toilet. L3 is farthest from the door, so the decrease in ammonia concentration is not significant. L6 is located near the toilet, and the ammonia concentration is also positively correlated with the height of the vent. In summary, the ammonia concentration in the toilet increases with the increase of the exhaust vent height, indicating that the change in the air outlet height has no significant effects on the indoor airflow pattern. The lower location of the vents is beneficial to the dilution of pollutants and improvement of indoor air quality.

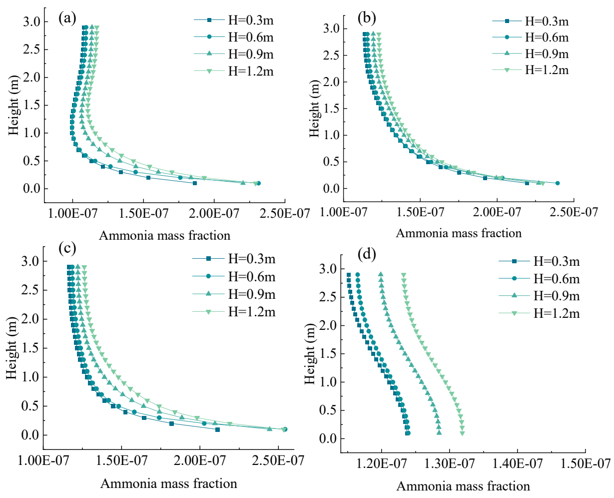



**Fig. 7.** Vertical ammonia concentration distribution curve under different air outlet heights: (a)L1; (b)L2; (c)L3; (d)L6.

### 3.3 Air quality

The values of the mean air of age(MMA), AEE, and ventilation effectiveness for Case1-8 are listed in Table 2. The worst MAA is displayed in Case 1 with the value of 659 s. The MAA of the toilet reaches a minimum value of 167s when the ACH is 20. The MAA at 1.5m is greater than at 0.9m, and the difference is in the range of 10-30s, which has few effect on the thermal comfort. The change of the vent position has limited effects on MAA. The AEE is almost independent of the ACH changes because the main factor affecting the AEE is the air distribution mode. With the same ACH, the lower the exhaust position, the smaller the AEE. It can be concluded that the low exhaust outlets are not beneficial to the entry of fresh air.

The magnitude of the ventilation efficiency is impacted by the locations of exhaust vents and ACH. The ventilation efficiency of four working conditions are less than 1, and the maximum and minimum values of ventilation efficiency are 0.99 (Case1) and 0.86 (Case4). As the height of the vent increases, the pollutant ventilation efficiency reduces continuously. When the height of the exhaust vents is 0.3 m, the maximum ventilation efficiency of 1.17 is obtained. The proper height of the vent installation is 0.3m, i.e., the vents is as close as possible to the source of pollution.

**Table 2.** Data for air quality evaluation

| Case | Mean air of age/s | | | AEE | ε |
|---|---|---|---|---|---|
| | H=0.9m | H=1.5m | Room | | |
| 1 | 636 | 674 | 659 | 0.55 | 0.99 |
| 2 | 318 | 341 | 334 | 0.54 | 0.94 |
| 3 | 209 | 226 | 223 | 0.54 | 0.90 |
| 4 | 154 | 169 | 167 | 0.54 | 0.86 |
| 5 | 123 | 228 | 234 | 0.51 | 1.17 |
| 6 | 219 | 254 | 242 | 0.50 | 1.16 |
| 7 | 213 | 236 | 229 | 0.52 | 1.12 |
| 8 | 205 | 230 | 225 | 0.53 | 0.98 |

## 4 Conclusions

In this paper, the diffusion characteristics of pollutants in public toilets are numerically studied under different ACHs and exhaust vent heights. Some valuable conclusions are obtained as follows:

(1) With the increase of ACH, the toilet pollutant concentration gradually reduces. when the ACH is >15, the pollutant concentration has a flat reducing trend. From aspects of the energy-saving and ventilation efficiency, the proper ACH is 15.

(2) When the exhaust vents are installed near the pollution sources, the pollutant concentration in the toilets gradually increases with the height of the vents, while the ventilation efficiency has an opposite variation trend.

## References

1. Y. Krishnamoorthy, et al., *Association between indoor air pollution and cognitive function among nationally representative sample of middle-aged and older adults in India-A multilevel modelling approach.* Indoor Air, **32**(1)(2022).
2. Z. Zhang, et al., *CFD Study on the Ventilation Effectiveness in a Public Toilet under Three Ventilation Methods.* Energies, **14**(24)(2021).
3. C. Sun, et al., *Indoor exposure levels of ammonia in residences, schools, and offices in China from 1980 to 2019: A systematic review.* Indoor Air, **31**(6): p. 1691-1706(2021).
4. A. Ameen, et al., *Experimental Investigation of the Ventilation Performance of Different Air Distribution Systems in an Office Environment-Cooling Mode.* Energies, **12**(7)(2019).
5. Y.-C. Tung, et al., *An experimental study on ventilation efficiency of isolation room.* Build. Environ., **44**(2): p. 271-279(2009).
6. Y.-C. Tung, S.-C. Hu, and T.-Y. Tsai, *Influence of bathroom ventilation rates and toilet location on odor removal.* Build. Environ., **44**(9): p. 1810-1817(2009).
7. Y.-C. Tung, et al., *Experimental performance investigation of ventilation schemes in a private bathroom.* Build. Environ., **45**(1): p. 243-251(2010).
8. S.-C. Chung, et al., *Natural Ventilation Effectiveness of Awning Windows in Restrooms in K-12 Public Schools.* Energies, **12**(12)(2019).
9. Y.-P. Lin, *Natural Ventilation of Toilet Units in K-12 School Restrooms Using CFD.* Energies, **14**(16)(2021).
10. C. Qin and W.-Z. Lu, *Effects of ceiling exhaust location on thermal comfort and age of air in room under impinging jet supply scheme.* J. Build. Eng., **35**(2021).
11. F. Contrada, et al., *A new method for air exchange efficiency assessment including natural and mixed mode ventilation.* Energy Build., **254**(2022).
12. C. Shen, N. Gao, and T. Wang, *CFD study on the transmission of indoor pollutants under personalized ventilation.* Build. Environ., **63**: p. 69-78(2013).