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Indoor Air Quality Improvement in Public Toilets at Railway Stations in China: A Field and Numerical Study

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Abstract: This study investigated the air quality and ventilation systems of 22 public toilets in 10 railway stations in China. Approximately 80% of public toilets meet the standard for ammonia concentration in Class I toilets, while 20% exceed the standard. It was found that the concentration of pollutants is mainly related to the number of toilet users and the ventilation system. In 20% of public toilets, the change in ammonia concentration was delayed by about 1 to 2 h with the change in hourly service number. In order to improve the air quality, a design method for calculating the number of toilet cubicles was proposed. Results show that the service capacity of the cubicle per hour (SCCH) of a female toilet is 12, the SCCH of male toilets is related to the ratio of squatting pans to urinals (RSU), which is suggested to be 1:1~1:0.8, and the corresponding SCCH is 16~20. Then, the effect of different ventilation forms was simulated by computational fluid dynamics (CFD) 2019 software. The results show that the bottom exhaust was better than the top exhaust and that the fresh air supply system is unnecessary. The recommended ventilation rate for toilets is 20 air changes per hour (ACH). The scale design method of toilets proposed in this paper was meant to address the gender imbalance and avoid queuing and provides a reference for the renovation and design of public toilets.

Keywords: air quality; ammonia concentration; ventilation system; public toilet; railway station

Citation: Yu, J.; Qian, C.; Zhao, J.; Tao, J.; Leng, K.; Xu, X. Indoor Air Quality Improvement in Public Toilets at Railway Stations in China: A Field and Numerical Study. *Sustainability* **2023**, *15*, 8720. https://doi.org/10.3390/su15118720

Academic Editor: Elisa Belloni

Received: 30 March 2023
Revised: 9 May 2023
Accepted: 23 May 2023
Published: 29 May 2023

1. Introduction

Railway travel is becoming more popular for its convenience and high speed. The railway station occupies a unique position in the urban environment as an important part of the city's utilities, and the level of service should be paid attention to [1,2]. In the first half of 2021, railways transported 1.365 billion passengers in China. With the development of the economy, creating a comfortable and sanitary environment for public toilets is a concern for people. Customer satisfaction is one of the key determinants for the quality of services [3]. According to a survey at a railway station in India, passengers expressed low satisfaction with the cleanliness of washrooms and toilets [4]. The main problems of public toilets are as follows: (1) strong odor and poor air quality; (2) significant queues during peak periods due to insufficient cubicles; (3) queues in female toilets due to the unreasonable ratio of male to female cubicles (RMFC). Currently, the concept of a toilet revolution is being proposed in China, which aims to provide a sanitary and comfortable space for users and prevent human excreta from polluting the environment [5–7]. The renovation and design of public toilets became a topic [8–10].

The purpose of this study is to improve the air quality of public toilets in railway stations and alleviate the queues in toilets. We conducted field research on the number of people using the toilet (service number) of a cubicle per day and the air quality of public toilets in 10 railway stations. The main contributions are as follows: (1) The typical pollutant (ammonia) concentration distribution of 22 public toilets in 10 railway stations was tested, and the influencing factors were analyzed. (2) Based on the peak hour departure quantum and the ratio of the male to female number (RMF), a design method for calculating the number of toilet cubicles is proposed. (3) The effect of different ventilation forms was investigated, and the ventilation mode and ventilation volume suitable for toilets in high-speed railway stations are put forward. Therefore, this study provides a reference for the design and renovation of public toilets and the improvement of air quality in railway stations of different sizes. Figure 1 shows the structure and research approach of this paper.

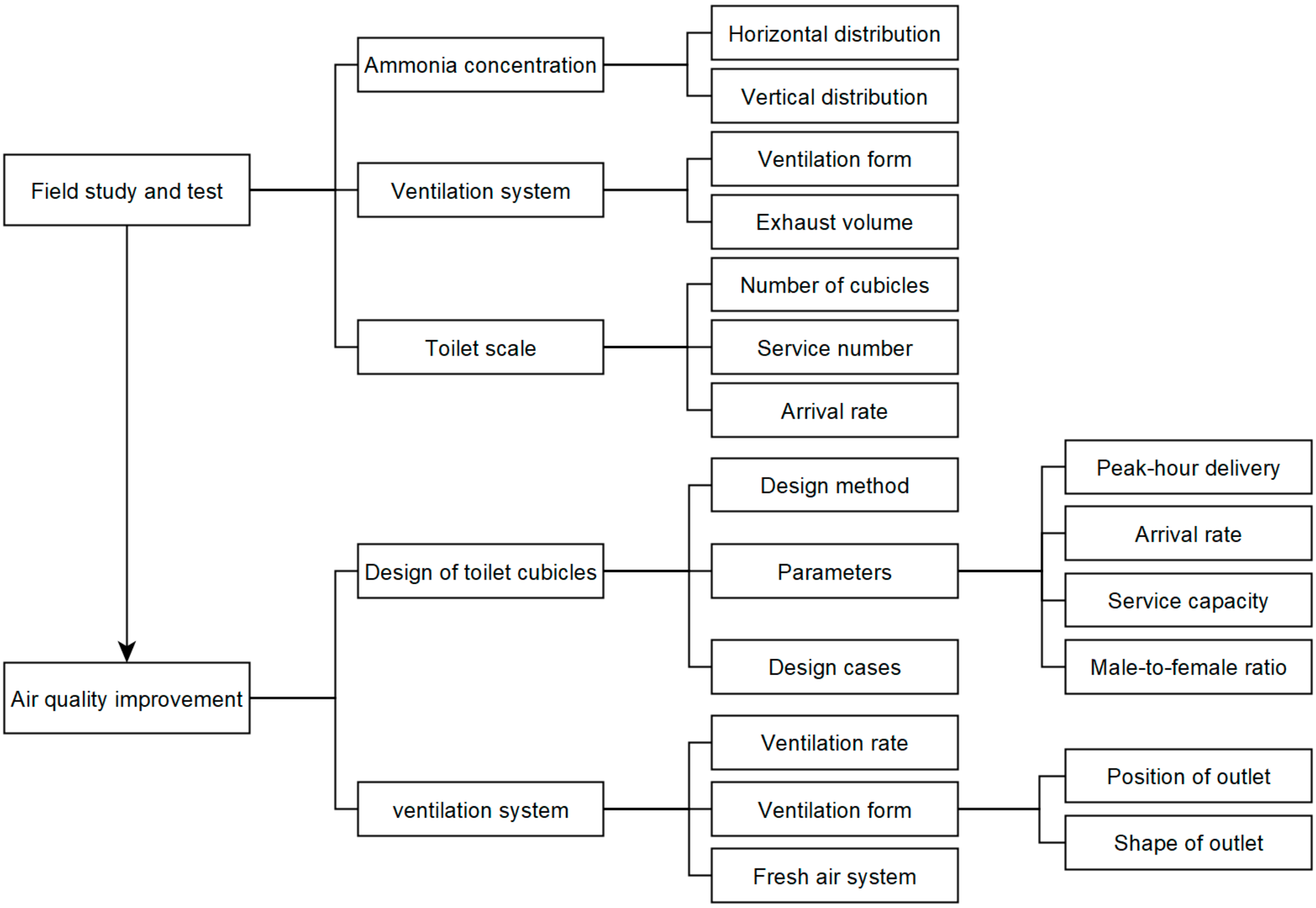


Figure 1. Frame diagram.

2. Literature Review

Public toilets in railway stations reflect the civilization of a city. Indoor air quality has a huge impact on the travel experience. For a long time, people thought that the smells in toilets were an inevitable phenomenon. However, modern toilets need to be beautiful and have good air quality. There needs to be an efficient ventilation system and a reasonable number of toilet cubicles. In the past three years, China has issued two important instructions on the 'toilet revolution', urging all of the country to take concrete measures to improve the toilet environment. There were queues for female toilets at some train stations. The reason may be that the cubicles are insufficient and the RMFC is unreasonable. Mechanical ventilation in the toilet can dilute the concentration of contaminants and keep the indoor air fresh. Therefore, it is particularly important to design an efficient ventilation system for toilets in public buildings.

Indoor pollutants have a great impact on human health [11–15]. Toilet flushing generates and spreads fecal aerosols [16]. The main pollutant in toilets is ammonia, which is produced by human excrement. Effective ventilation systems can improve indoor air quality [17–19] and reduce the spread of viruses [20,21]. Lee et al. [22] investigated 61 public toilets and recommended that ventilation and cleaning should be improved to mitigate the risk of cross infection in public toilets. The ventilation rate should be strongly based on the strength of the pollutant sources [23], and higher ventilation rates reduce odor dispersion [17]. Zhang et al. [24] investigated the effect of the position of the exhaust fan and the air change rates on the concentration of pollutants in the toilet; the ammonia concentration reaches a minimum at ACH = 10 h^{-1}. Tung et al. [25] investigated the influence of ventilation schemes on unpleasant odor removal. The results showed that the ventilation performance ranged from high to low for the three ventilation schemes in the bathroom: (1) forced-ceiling-supply and wall-exhaust systems; (2) forced-ceiling-supply and ceiling-exhaust systems; and (3) natural-window-inlet and forced-ceiling-exhaust systems. Chung et al. [26] proved that a floor exhaust ventilation system can efficiently purge the odor from polluted sources and improve air quality in the lavatory environment. Reasonably, the use of natural ventilation can improve indoor air quality [27–29]. However, it is difficult to maintain a sufficient natural ventilation rate via passive design, and improving the ventilation efficiency of toilets with the aid of simple and energy-saving mechanical ventilation is worth further research [30]. Ao et al. [31] analyzed the concentration distribution law of pollutants in the bathroom with and without mechanical ventilation and found that the toilet-side exhaust can reduce the extent of pollutant dispersion significantly. Zhao et al. [32] compared the effects of a primary air fan-coil system and an all-air air conditioning system on indoor pollutant diffusion and found that the ventilation design of an all-air air conditioning system with an exhaust height of 400 mm can remarkably improve the indoor environmental health and ventilation efficiency of public toilets. Li et al. [33] concluded based on CFD analysis that the pollution emission from mobile public toilets is best done in the form of upper supply and down exhaust. The temperature increased by 1 °C, and the ammonia concentration increased by 0.036 mg/m^3. Due to the large passenger flow in railway stations, queuing at public toilets is common. The biological needs of women regarding toilets are different from those of men, especially during pregnancy and menstruation [34–36]. However, the service care for particular groups (the disabled, women, infants, etc.) in urban public toilet facilities is still under-recognized [37]. The phenomenon of queuing in female toilets but vacancy in male toilets shows the problem of an imbalanced RMFC. Yan et al. [38] investigated 100 public toilets in the Hutong neighborhoods of Beijing; the results showed that approximately 34% of female toilets have 1-2 more squatting pans than male toilets and that there is a huge gap to be filled against the gender imbalance. Afacan et al. [39] conducted a survey of 14 public toilets in Turkey and found that women's toilets are fewer in number and smaller in size compared to men's. In Britain, there is the problem of inadequate public toilet provision and gender inequality in facilities [40]. Sun et al. [41] investigated public toilets in crowded places in Changsha and suggested that the RMFC should be 1:1.7. Huh et al. [42] reveal that the current standard fails to achieve gender equality at restrooms by using a quantitative model.

At present, the impact of the ventilation system in public toilets, including the shape and position of air outlets, on air quality is neglected. Most of the existing studies are on individual toilets, not on public restrooms with multiple cubicles. There is a lack of research on the indoor air quality and ventilation systems of toilets in large public places.

3. Indoor Air Quality of Toilet

3.1. Research Subjects

According to Standard TB10100-2018 [43], the investigated stations are divided into large stations (≥5000 people), medium stations (≥1000 people), and small stations (<1000 people) by the actual peak hour departure quantum. According to the peak hour departure quantum provided by the station, the scales of the 10 stations surveyed are classified, as shown in Table 1. The selected stations are all located in the hot-summer and cold-winter zones in China, and the locations are marked on the map (Figure 2).

The standard GB/T17217-1998 [44] in China divides public toilets into three categories according to the concentration of pollutants. The standard TB10100-2018 [43] has provisions on the settings of cubicle number and ventilation volume, as shown in Table 2.

Table 1. Peak hour departing quantum of different railway stations.

Scale	Large Station				Medium Station			Small Station		
Station	SHHQ	HZD	NJ	SZ	WZN	LYG	ZJ	KS	QDH	SZXQ
Peak hour departing quantum	17,395	18,653	6569	6016	4209	1381	1320	763	206	<200

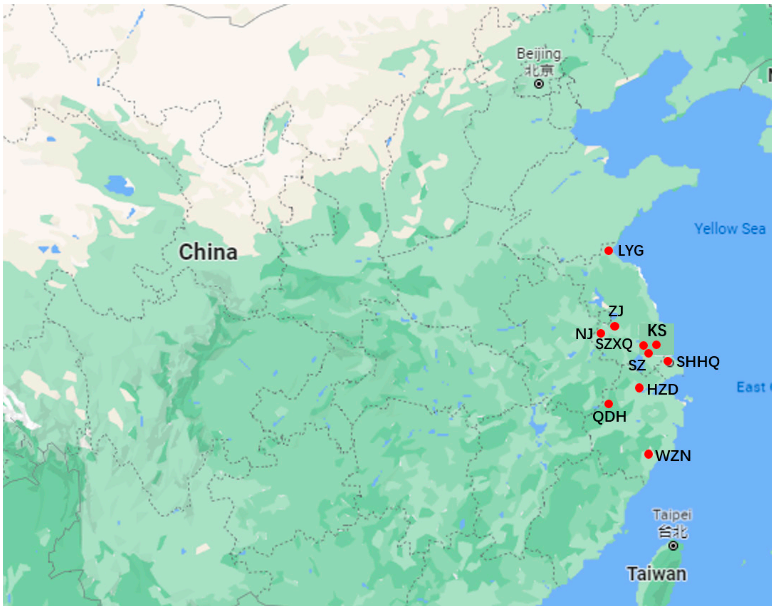


Figure 2. The location of the investigated railway station.

Table 2. Toilet design standards.

Standards	Parameters	Values		
Hygienic standard for communal toilet in city (GB/T17217-1998) [44]	Type of water-flush public toilet	Class I	Class II	Class III
	Ammonia concentration (ppm)	0.395	1.318	3.95
	Hydrogen sulfide concentration (ppm)	0.0066	0.0066	0.0066
Standard for design of urban public toilets (CJJ14-2016) [45]	Type	Male toilet	Female toilet	
	Service number (people/cubicle · day)	150	100	
	Number of cubicles	2 (<100 males); 1 for every additional 60 males	4 (<100 females); 1 for every additional 30 females	
	Ventilation	$40\ m^3/h$ for each squatting pan; $20\ m^3/h$ for each urinal; Ventilation rate is not less than 5 ACH		
Code for design of railway passenger stations (TB10100-2018) [43]	Number of cubicles	2.5 cubicles for every 100 people; RMFC should be 1:2		
	Ventilation rate	15~20 ACH		

3.2. Field Study

The indoor air quality and ventilation of public toilets in the waiting halls of the 10 railway stations were measured in January 2021. Ammonia and hydrogen sulfide are the main pollutants in toilets. Hydrogen sulfide concentrations were all lower than the standard specification (0.0066 ppm) in the toilet of the tested station, and most of them were 0, so this paper uses ammonia as a pollutant representative to analyze the indoor air quality. According to the building structure and function partition of the toilet, the measuring points are evenly distributed in the urinal area, stool area, aisle, and corner. First, the pollutant concentration of all measuring points at 0.9 m was measured, and the measuring point with the highest concentration was recognized as the worst point. Then the ammonia concentrations of the points at 0.3 m, 0.9 m, and 1.7 m were measured hourly.

The ventilation forms and exhaust volume were surveyed. Based on the air velocity measured by the TSI 9565 anemometer, the exhaust volume can be calculated by multiplying the mean air velocity by the area. Ammonia concentration is measured by a PLT400-2 composite detector. The passenger flow counter monitors the number of people entering and leaving the toilet over a 24-h period. The number of passengers at the station is provided by the station gate. The basic information about the test instruments is shown in Table 3. The TSI 9565 anemometer and PLT400-2 composite detector record data manually, and the passenger flow counter records data automatically, which can be downloaded from mobile phones or computers. Other instruments include handheld records.

Table 3. Main measuring instruments.

Instruments	Parameter	Precision (Measuring Range)
TSI 9565 anemometer	Air velocity Air temperature	±0.06 m/s (0–3.0 m/s); ±0.2 m/s (3.1–30 m/s) ±0.3 °C
PLT400-2 composite gas detector	Ammonia concentration	0.01 ppm (0–10 ppm)
Passenger flow counter	Number of people	-

3.3. Results and Disicussion of Air Quality Status Survey

3.3.1. Ammonia Concentration

According to Standard GB/T17217-1998 [44], the maximum ammonia concentration is 0.395 ppm for Class I toilets, 1.318 ppm for Class II toilets, and 3.95 ppm for Class III toilets. We tested the ammonia concentrations in the male and female toilets, and compared the average values to evaluate the air quality of toilets in different stations, as shown in Figures 3 and 4. The average ammonia concentrations range from 0.02 to 2.04 ppm and 0.01 to 0.37 ppm in male and female toilets, respectively. Approximately 80% of toilets can meet the standard of Class I toilets, which reflects the good ventilation system and operation management of toilets. The ammonia concentration of the male toilet was significantly higher than that of the female toilet, except at SZ and WZN station, which may because the urine stains on the ground were not cleaned in time. Due to the large service number and the inefficient ventilation system, the average ammonia concentration of the unrenovated toilets (HZD(U)) in HZD station was 1.38 ppm, and the highest was 3.05 ppm. However, the average ammonia concentration in renovated toilets (HZD(R)) in HZD station was 0.46 ppm, and the highest was 0.51 ppm. It can be seen that a good ventilation system greatly improves the air quality and reduces the ammonia concentration in the toilet. The average ammonia concentration at KS station was 2.04 ppm, and the highest was 4.22 ppm due to the small space for toilets and the failure of ventilation facilities.

The ammonia concentration in female toilets is evenly distributed on the horizontal plane. In order to investigate the regularity of the ammonia concentration on the horizontal distribution of the male toilet, we tested the ammonia concentrations in the stool and urinal areas at a height of 0.9 m (Figure 5). In large stations (SHHQ, NJ, and SZ), ammonia concentrations in the urinal area were about twice as high as they were in the stool area, mainly due to the large service numbers in urinal areas and the urine stains on the ground that could not be cleaned in time. In medium and small stations (WZN, LYG, ZJ, QDH, and SZXQ), ammonia concentrations in the urinal area are basically the same as that in the stool area. This is because urinals are used relatively infrequently, and the sweeping of the toilets effectively reduces the volatilization of urine stains on the ground. In the stations with poor toilet ventilation systems (HZD(U), KS), the ammonia concentration in the stool area was significantly higher than those in the urinal area because the ventilation system was extremely ineffective and the ammonia emitted by feces accumulated in the toilets. Therefore, it is suggested that the cleaning frequency of urinal area be increased in large stations and that the toilets with poor ventilation be renovated as soon as possible. Increasing exhaust air volume can greatly reduce the overall ammonia concentration in toilets.

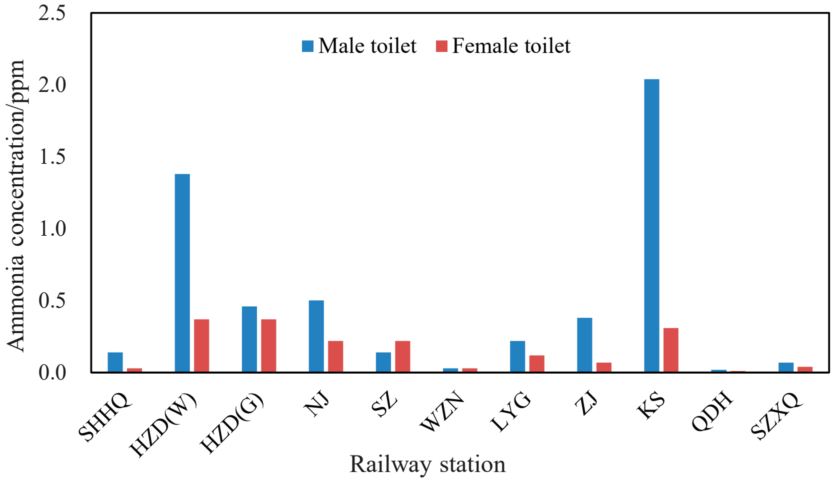


Figure 3. Average ammonia concentration of toilets.

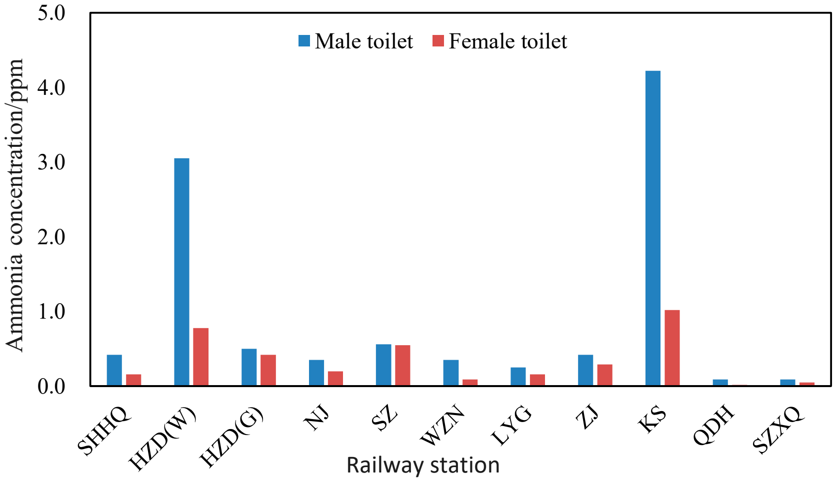


Figure 4. Maximum ammonia concentration of toilets.

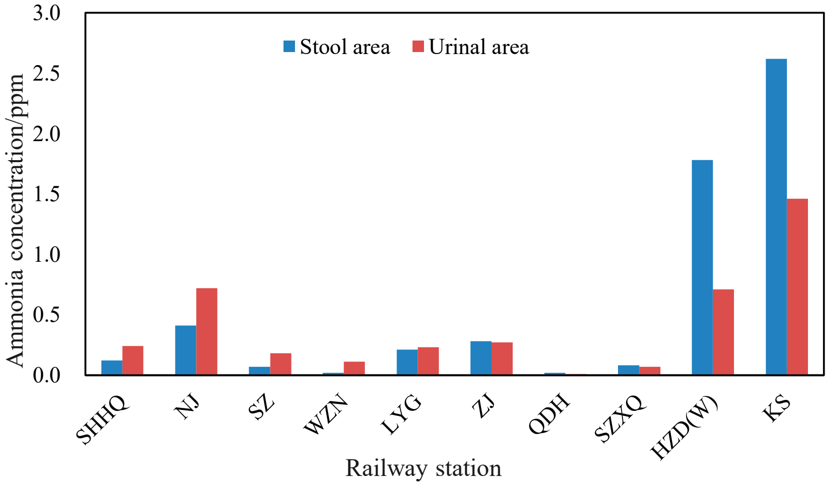
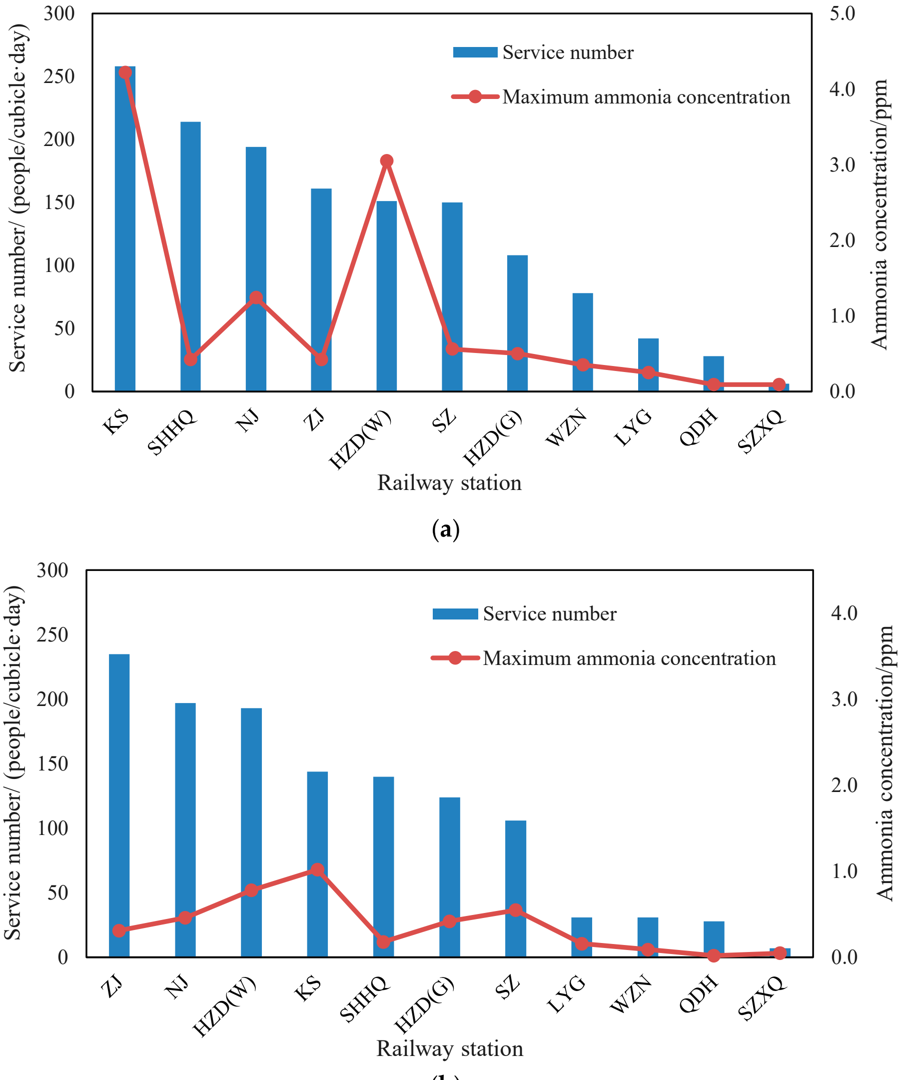


Figure 5. Average ammonia concentrations in stool and urinal areas of male toilets.

The test data show that the ammonia concentrations at 0.3 m, 0.9 m, and 1.7 m are almost the same. Compared with air, ammonia has a smaller molecular mass and a lower density. Theoretically, ammonia will flow upward after volatilization. The ammonia concentration in toilets is greatly affected by the movement of people, the cleaning frequency, the measuring position, and the ventilation form, so the ammonia concentration measured at different heights has no obvious stratification or distribution regularity in the vertical direction.

To analyze the factors influencing ammonia concentration, the relationship between the average daily service number of a cubicle and the maximum ammonia concentration at the measurement point was tested and analyzed, as shown in Figure 6. For toilets with poor ventilation, such as KS station and HZD (U) station, the maximum ammonia concentration is much higher than at other stations. For toilets with good ventilation, the average daily service number of a cubicle has a significant influence on the maximum concentration of ammonia. When the service number is less than 100 people/(cubicle · day), the ammonia concentration in the toilet decreases with the decrease in service number. When the service number is more than 100 people/(cubicle · day), it does not meet the standard of Class I toilets, except for the female toilets in SHHQ and ZJ station. The maximum ammonia concentrations in the female toilets were only 0.18 ppm at SHHQ station and 0.31 ppm at ZJ station due to the high frequency of cleaning when the test was conducted.



(**a**)

(**b**)

Figure 6. Daily service number and maximum ammonia concentration: (**a**) male toilet; (**b**) female toilet.

In the case of the WZN and KS stations, the change in the ammonia concentration of toilets will be delayed by about 1 to 2 h along with the change in the hourly service number of a cubicle (Figure 7). The cleaning frequency has a great impact on the ammonia concentration. There is a great difference between the data measured at the beginning of cleaning and after cleaning for a while. There is no strong correlation between the hourly service number and ammonia concentration in other stations, possibly because there is a difference in the cleaning frequency and methods.

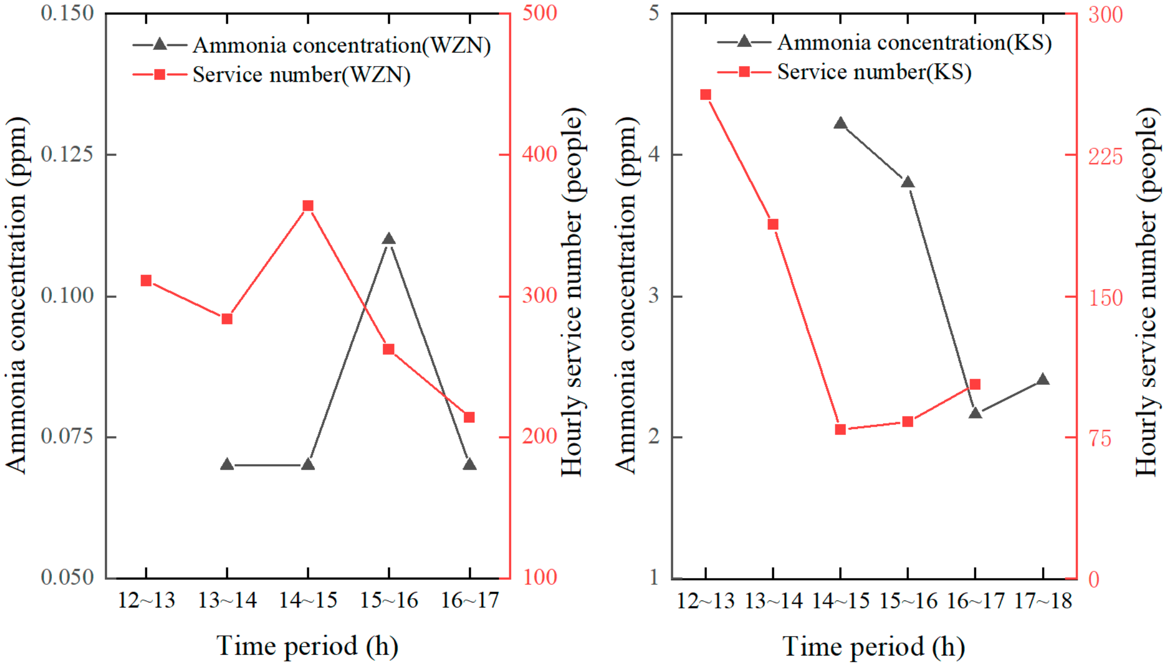


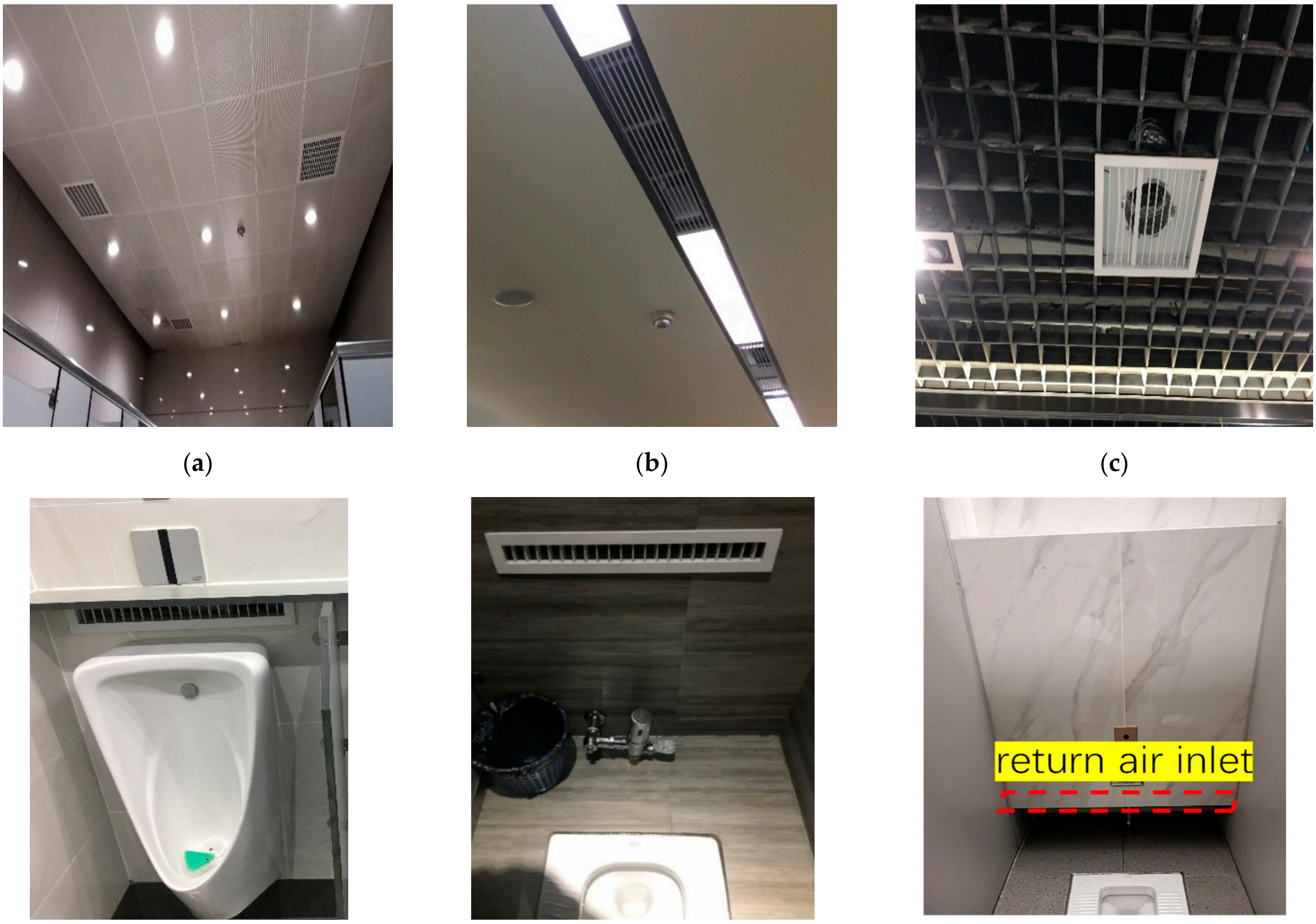
Figure 7. Hourly service number and ammonia concentration of male toilets in WZN and KS stations.

3.3.2. Ventilation System

In order to find out the pollutant removal capability, the ventilation systems in the toilets were investigated, and the different air vents were photographed, as shown in Figure 8. There are two ventilation forms in the surveyed toilets. One is the mechanical exhaust system, including the vents of a square single-layer shutter and the rectangle single-layer shutter on the top (Figure 8a,b), and a rectangle vent at the bottom (Figure 8d–f). In eight of the 10 stations, the toilets use this system, with exhaust vents located on top of the toilets. The other is a mechanical air supply and exhaust system. In two of the ten stations (NJ station and ZJ station), the toilets adopt this system, with the fresh air outlets located at the top of the toilet (as shown in Figure 8c) and the exhaust vent at 0.8 m above the ground.

Standard TB10100-2018 [43] stipulates that the ventilation rate of toilets should be between 15 and 20 ACH. We calculated the ventilation rate of the toilets by testing the air velocity of the door, as shown in Figure 9. Approximately 73% of the surveyed toilets were ventilated at less than 15 ACH, which did not meet the requirements. In QDH station, the outside window of the male toilet was closed while the outside window of the female toilet was opened, leading to a large difference in ventilation rate between the two toilets. In other stations, the ventilation rates of male and female toilets were close, which was consistent with the actual situation.

The improvement of ventilation rates can effectively improve the indoor air quality of toilets. HZD station has two types of toilets: renovated and unrenovated. There is little difference in the size of the toilet, the number of services, and the frequency of cleaning, but the ventilation rate of the renovated toilet increased significantly. Table 4 shows that the maximum ammonia concentration decreased from 3.05 ppm to 0.5 ppm in male toilets and decreased from 0.78 ppm to 0.42 ppm in female toilets with the increase in ventilation rate.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 8. Ventilation system: (**a**) Square vent at the top (HZD); (**b**) Rectangle vent at the top (HZD(G)); (**c**) The fresh air outlet at the top (NJ); (**d**) Rectangle vent at bottom (NJ); (**e**) Rectangle vent at bottom (0.8 m) (ZJ); (**f**) Rectangle vent at bottom (0.3 m) (HZD(G)).

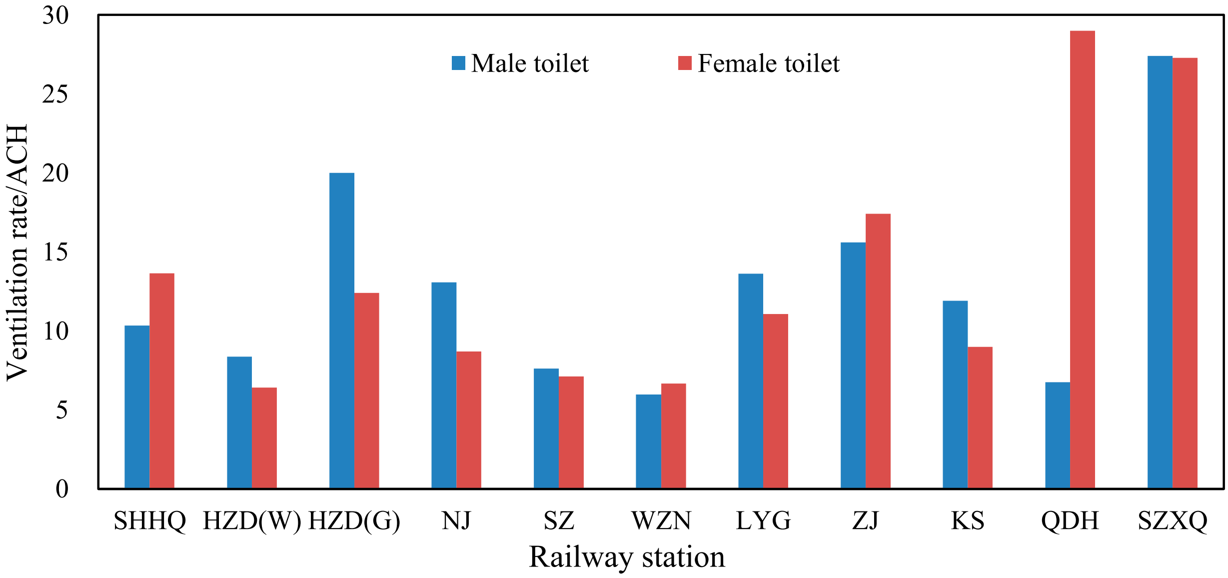


Figure 9. Ventilation rate of toilets.

Table 4. Effect comparison of HZD station's toilet before and after renovation.

Type		Service Number (People/Cubicle · Day)	Ventilation Rate (ACH)	Maximum Ammonia Concentration (ppm)
Male toilet	Unrenovated	151	8.4	3.05
	Renovated	108	20.0	0.5
Female toilet	Unrenovated	193	6.4	0.78
	Renovated	124	12.4	0.42

4. Air Quality Improvement

4.1. Toilet Scale

The air quality in the toilet is affected by the size of toilet. The number of male and female cubicles was investigated, and the RMFC was calculated. The results are shown in Table 5. The urinal in the male toilet was regarded as a cubicle during the survey. The result shows that male cubicles are more abundant than female cubicles because more urinals can be installed in the same area. According to the investigation, the highest RMFC is 1.48:1, and the average RMFC is 1.35:1, resulting in the phenomenon of male toilets being free while female toilets are occupied. So, the number of female cubicles should be increased.

Table 5. The scale of public toilets in railway stations.

Station	Large Station				Medium Station			Small Station		
	SHHQ	HZD	NJ	SZ	WZN	LYG	ZJ	KS	QDH	SZXQ
Number of male cubicles (Including urinals and squatting pans)	293	207	185	167	150	65	53	56	31	10
Number of female cubicles	235	144	125	130	116	46	36	40	29	7
Total cubicles	528	351	310	297	266	111	89	106	60	17
RMFC	1.25	1.44	1.48	1.28	1.29	1.41	1.47	1.4	1.06	1.43

4.1.1. Service Capacity

Service capacity of a cubicle per hour (SCCH) refers to the maximum number of cubicles that can be used per hour. When there are more people than the toilets can serve, the toilets line up. The service number of toilets at each station was counted, as shown in Table 6. The service number of toilets in SZ, WZN, LYG, QDH, and SZXQ stations was relatively small, which means the number of people going to the toilet is far lower than the service capacity. The service number of toilets in SHHQ, HZD, NJ, ZJ, and KS stations was high, and SCCH was determined by analyzing the queuing situation.

Table 6. The service number (people/(cubicle · hour)).

Station	SHHQ	HZD (U)	HZD (R)	NJ (S)	NJ (N)	SZ	WZN	LYG	ZJ	KS	QDH	SZXQ
Male toilet	20.2	13.2	9.5	12.4	18.8	9.4	9.4	8.8	16.8	23.5	3.3	1.8
Female toilet	12.7	15.5	10.4	15.8	9.3	7.5	2.9	6.2	26	11.7	3.4	3.1

Note: (U)—Unrenovated toilet; (R)—Renovated toilet; (S)—South toilet; (N)—North toilet.

For female toilets, the unrenovated toilet at HZD station and the south toilet at NJ station lined up when the service numbers were more than 14.6 and 12.2 people/(cubicle · hour), respectively. To obtain the appropriate SCCH, the effect of the hourly service number on queuing was analyzed (Table 7). As a result, the hourly service number should be no more than 12 to avoid queuing.

Table 7. Hourly service capacity and queuing situation in female toilet.

Station	Service Number (People/(Cubicle · Hour))	Queuing Situation
HZD(R)	14.67 (15:00~16:00) 14.96 (16:00~17:00) 15.08 (13:00~14:00) 15.50 (14:00~15:00)	Sometimes Sometimes Frequently Frequently
NJ(S)	12.17 (19:00~20:00) 13.92 (11:00~12:00) 15.75 (14:00~15:00)	Sometimes Sometimes Frequently
SHHQ	<12.7	NO
HZD(U)	<10.2	NO
NJ(N)	<9.3	NO
KS	<11.7	NO

For male toilets, the ratio of squatting pans to urinals (RSU) has a great impact on SCCH, as defecation time is longer than urination time and the queue is mainly concentrated in the stool area. According to the investigation shown in Table 8, male toilets in HZD(U), KS, and NJ(S) stations lined up in the stool area. When RSU is 1:1, the maximum hourly service number of a cubicle is 16 to avoid queuing. When RSU is less than 1:1, SCCH reduces; otherwise, SCCH increases. When the RSU is 1:0.82–1:1 in male toilets, the maximum hourly service number of a cubicle is 20 in male toilets. To design the number of toilets, this study concluded the recommended RSU and SCCH, which are presented in Table 9.

Table 8. Service capacity of a cubicle and queuing situation in male toilet.

Station	RSU	Service Number (People/(Cubicle · Hour))	Queuing Situation
HZD(U)	1:1.6	10.81 (13:00~14:00) 13.22 (14:00~15:00)	Sometimes (in stool area) Sometimes (in stool area)
KS	1:1	16.6 (12:00~13:00) 16.7 (11:00~12:00) 17.4 (22:00~23:00) 18.8 (23:00~24:00)	Sometimes (in stool area) Sometimes (in stool area) Sometimes (in stool area and urinal area) Sometimes (in stool area and urinal area)
NJ(N)	1:1	18.8 (12:00~13:00)	Sometimes (in stool area)
SHHQ	1:0.82	20.19	Sometimes (in stool area)
HZD(R)	1:2	<9.55	No
NJ(S)	1:1	<12	No
others	-	<9.43	No

Table 9. Recommended service capacity of toilet.

Parameters	RSU	SCCH
Male toilet	1:1 1:0.9 1:0.8	16 18 20
Female toilet	-	12

4.1.2. Design of the Number of Toilets

The scale of the toilet is determined by the peak hour departure quantum of the station. The number of cubicles in the male toilet (N_m) and the female toilet (N_w) can be calculated by the following expressions:

$$N_\mathrm{m} = \frac{PH \times R \times \alpha_\mathrm{m}}{C_\mathrm{m}} \tag{1}$$

$$N_w = \frac{PH \times R \times \alpha_w}{C_w} \tag{2}$$

where PH is the peak hour departure quantum, as shown in Table 1. R is the ratio of the service number to departure quantum (toilet arrival rate) during the peak hour, which is calculated from the measured data (Figure 10). The ratio of the large station was 0.22 to 0.56, with an average of 0.43. The ratio of the medium station was 0.35 to 0.45, with an average of 0.41. The ratio of the small station was 0.71 to 0.99, with an average of 0.85. α_m and α_w are the ratio of male and female to total arrivals, respectively, ($\alpha_m + \alpha_w = 1$). C_m and C_w are the SCCH of male and female toilets, respectively.

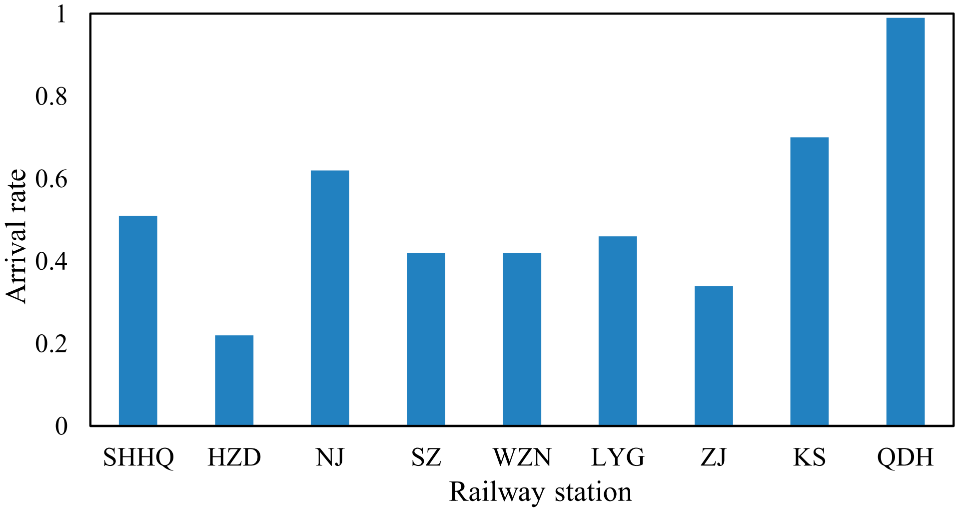


Figure 10. The toilet arrival rates during the peak hour.

The ratio of the service number of male to female toilets within a day (RMF) is obtained based on the measured service numbers of male and female toilets, as shown in Figure 11. RMF at 10 stations was 1.07 to 2.56, and the average is 1.7. RMF at HZD and QDH station was close to 1:1, but RMF at other stations was much higher than 1:1. The current standards, such as Standard CJJ14-2016 [45], Standard GB50226-2007 [46], and Standard TB10100-2018 [43], are all designed based on an RMF of 1:1, which is smaller than the actual survey data.

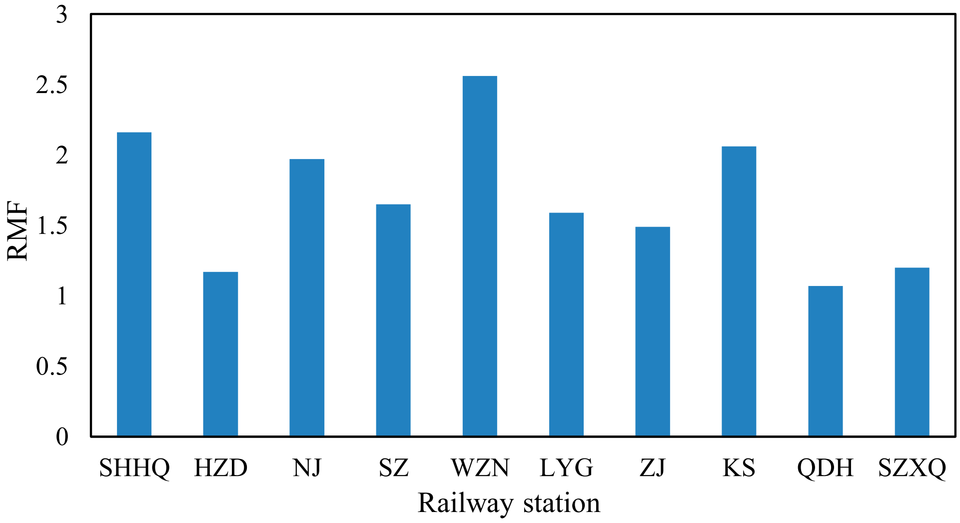


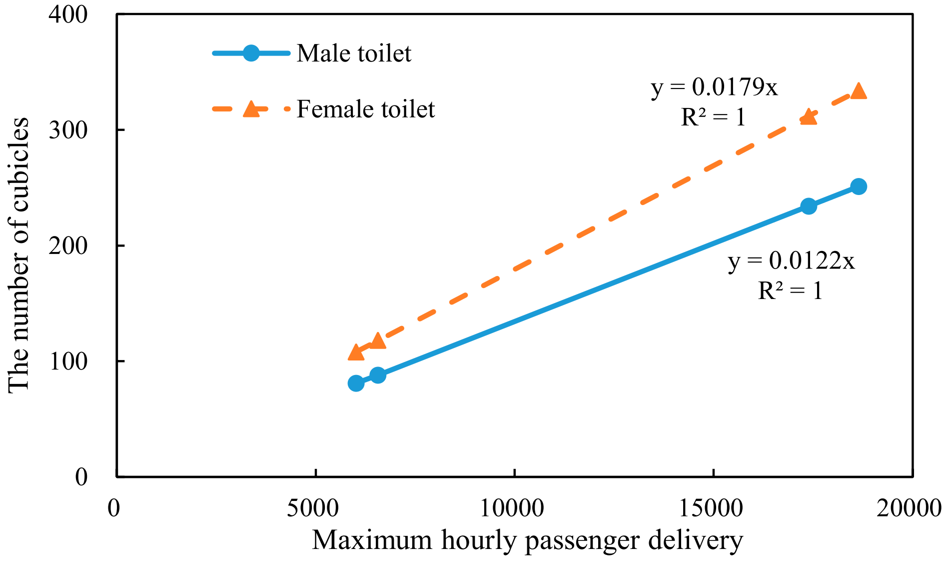
Figure 11. The ratio of service number of male to female.

According to the current standard and the above analysis, RMF is supposed to be 1:1 and 2:1, RSU takes 1:1, SCCH of female and male toilets is 12 and 16, respectively, and the toilet arrival rate takes the average (large station takes 0.43, medium station takes 0.41, and the small station takes 0.85). The male and female toilets at the surveyed stations are designed as shown in Table 10.

Table 10. Scale design of public toilet in railway stations.

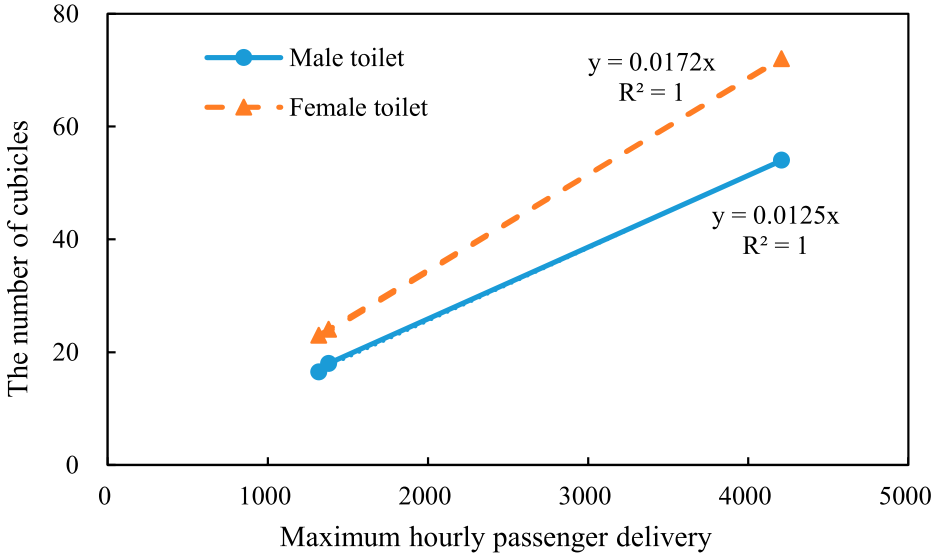
Station	**Large Station**			**Medium Station**				**Small Station**	
	SHHQ	**HZD**	**NJ**	**SZ**	**WZN**	**LYG**	**ZJ**	**KS**	**QDH**
Peak hour departure quantum	17,395	18,653	6569	6016	4209	1381	1320	763	206
Peak hour service number	7480	8021	2825	2587	1726	566	541	649	175
SCCH (male)					16				
SCCH (female)					12				
Number of male cubicles (actual)	293	207	185	167	150	65	53	16	31
Number of female cubicles (actual)	235	144	125	130	116	46	36	11	29
RMF is 1:1									
Peak hour service number (male)	3740	4010	1412	1293	863	283	271	324	88
Peak hour service number (female)	3740	4010	1412	1293	863	283	271	324	88
Number of male cubicles (calculated)	234	251	88	81	54	18	17	20	5
Number of female cubicles (calculated)	312	334	118	108	72	24	23	27	7
RMF is 2:1									
Peak hour service number (male)	4987	5347	1883	1725	1150	377	361	432	136
Peak hour service number (female)	2493	2674	942	862	575	189	180	216	58
Number of male cubicles (calculated)	312	334	118	108	72	24	23	27	9
Number of female cubicles (calculated)	208	223	78	72	48	16	15	18	5

This design basically alleviates the congestion of the public toilets in large stations and reduces the number of cubicles in medium and small stations with abundant cubicles. The relationship between the designed number of toilet cubicles in different stations and peak hour departure quantum is analyzed (Figure 12), and the formula for calculating the number of toilet cubicles is obtained, as shown in Table 11.

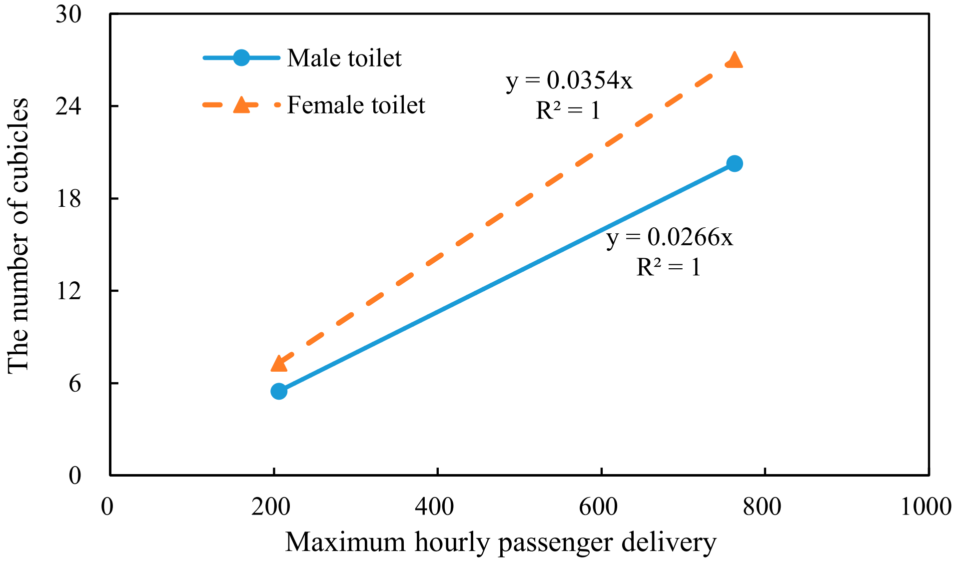


(**a**)

Figure 12. *Cont.*



(**b**)



(**c**)

Figure 12. The number of designed toilet cubicles (RMF of 1:1): (**a**) Large station; (**b**) Medium station; (**c**) Small station.

Table 11. The calculation formula for the number of toilet cubicles.

Station	Male Cubicles	Female Cubicles
Large station	y = 0.0122x	y = 0.0179x
Medium station	y = 0.0125x	y = 0.0172x
Small station	y = 0.0266x	y = 0.0354x

y—the number of toilet cubicles. x—peak hour departing quantum.

4.1.3. Recommended RMFC

The main factors affecting RMFC are the maximum hourly service number and the RMF and RSU in male toilets. The RMFC was calculated by the maximum hourly service number, SCCH, RSU, and RMF; the results are shown in Table 12. When RMF is 1:1, the recommended RMFC is 1:1.33–1:1.67. The RMFC should be determined according to the actual RMF and SCCH. According to the standard GB50226-2007 [46], RMF takes 1:1, RSU of male toilets takes 1:1, and the suggested RMFC is 1:1.33. For male toilets, SCCH can be improved by 10% when RSU increases to 1:0.8, and the appropriate RMFC is 1:1.67. Therefore, the RMFC of 1:2 stipulated in Standard TB10100-2018 [43] is not appropriate.

Table 12. Recommended RMFC.

RSU	**SCCH**	**RMFC**				
		RMF of 1:1	**RMF of 1.5:1**	**RMF of 2:1**	**RMF of 2.5:1**	**RMF of 3:1**
1:1	16	1: 1.33	1: 0.89	1: 0.67	1: 0.53	1: 0.44
1:0.9	18	1: 1.50	1: 1.0	1: 0.75	1: 0.60	1: 0.50
1:0.8	20	1: 1.67	1: 1.11	1: 0.83	1: 0.67	1: 0.56

After investigation and analysis, it was found that the ventilation systems of several railway stations have a poor effect, resulting in high pollutant concentrations. This section studies the effects of the ventilation volume and the location of the exhaust vent on the mean age of air and ammonia concentration by CFD simulation and gives suggestions for the design of the ventilation systems at public toilets.

4.2. Ventilation Optimization

4.2.1. Method and Basic Model

The CFD numerical simulation method is used to optimize ventilation and improve indoor air quality. Fluent is used. Figure 13 shows the basic model, which is 9.5 m × 9.0 m × 3.0 m (length × width × height). The urinal area is 9.0 m × 3.5 m × 3.0 m (length × width × height), and the spacing between urinals is 0.8 m. The stool area is 9.0 m× 6.0 m × 3.0 m (length × width × height), and the size of a cubicle is 1.8 m × 1.0 m (length × width). In the basic model, exhaust vents are evenly arranged on the ceiling, including 4 exhaust vents in the urinal area and 7 exhaust vents in the stool area. The size of the exhaust vents is 200 mm × 200 mm.

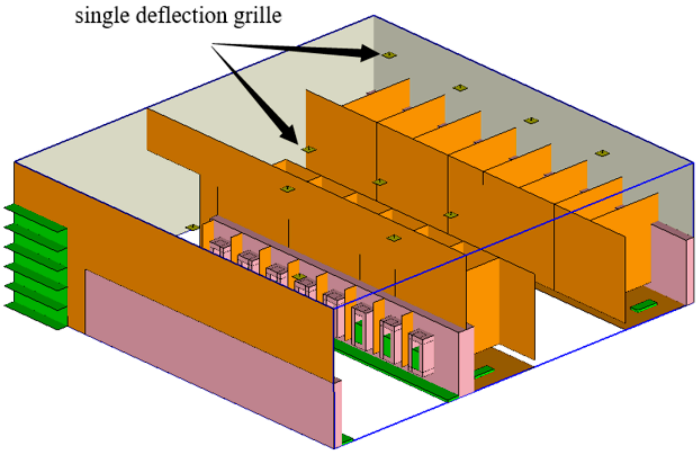


Figure 13. CFD model of male toilet in railway station.

The concentration mathematic equations in the simulation:

Equation of mass continuity [47]:

$$\frac{\partial_{\rho}}{\partial t^{2}} + \frac{\partial}{\partial x_i}\left(\rho u_i\right) = 0 \tag{3}$$

where ρ is density, t is time, and u is speed.

Momentum equation [47]:

$$\frac{\partial}{\partial_t}(\rho u_i) + \frac{\partial}{\partial x_i}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial_{\tau_{ij}}}{\partial x_j}\rho g_i \tag{4}$$

where p is pressure and τ is shear stress.

Energy equation [47]:

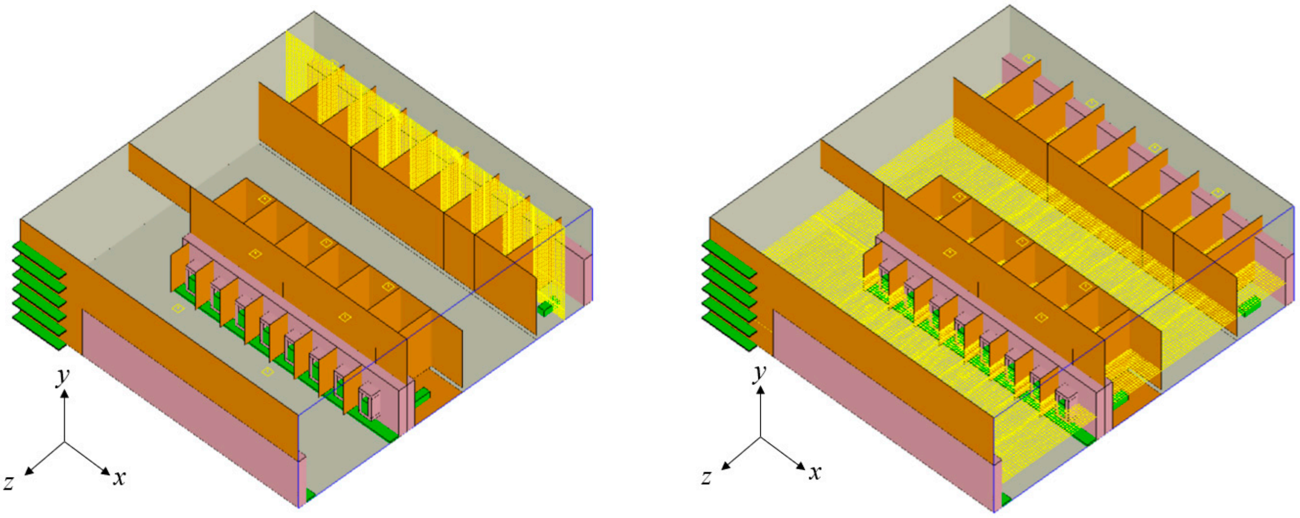
$$\frac{\partial_e}{\partial_t} + u_x \frac{\partial_e}{\partial_x} u_y \frac{\partial_e}{\partial_y} + u_z \frac{\partial_e}{\partial_z} = \frac{\lambda}{\rho} \nabla^2 T + q + \Phi \tag{5}$$

where e is an internal energy, λ is thermal conductivity, T is a temperature, and q is heat source per unit volume.

The mean age of air was selected to evaluate the ventilation effect, which reflects the freshness of indoor air. Other air quality evaluation indexes, such as ventilation efficiency (ratio of actual dilution air volume to ventilation volume delivered to the room), can be derived from the mean age of air. In addition, the distribution of ammonia concentration as the typical pollutant in toilets was simulated.

4.2.2. Mesh Generation and Independence Analysis

The meshing of the field was carried out using a hexahedral structural mesh, as shown in Figure 14. In order to ensure the accuracy and feasibility of the numerical simulation, the grid of the model needs to be properly optimized. The grid independence verification with a condition of 20 ACH is shown in Table 13.



(**a**) (**b**)

Figure 14. Structured mesh of computational domain: (**a**) XZ plane view; (**b**) XY plane view.

Table 13. Mesh sensitivity.

Meshing	**Number of Cells**	**Averaged Ammonia Concentration**		**Mean Age of Air**	
		Concentration (ppm)	**Relative Error**	**Age of Air (s)**	**Relative Error**
Coarse	501,326	3.65	5.49%	223	−9.72%
Middle	712,383	3.26	−5.78%	231	−6.48%
Fine	979,409	3.53	2.02%	253	2.43%
Finest	1,274,488	3.46	-	247	-

Four different grid numbers were chosen for the corresponding simulations: 501,326, 712,383, 979,409, and 1,274,488. Simulations with the same parameter settings and boundary conditions are performed. Comparing the average ammonia concentration and mean age of air at 0.9 m, the results show that 979,409 grids are sufficient to achieve grid independence, and the relative errors of ammonia concentration and age of air are less than 5%. Therefore, the 979,409 grid was chosen.

4.2.3. Verification of Turbulence Models

The RNG k-ε model uses the renormalization group (RNG) theory to derive the model equations. The RNG theory provides a more accurate description of the turbulence structure than the standard k-ε model. The RNG k-ε model is used. It is validated by the experimental data from the female toilet at Kunshan station. The ventilation rate of the model is set to the measured value of 9 ACH. The ammonia diffusion rate of squatting pans was set at 5×10^{-5} g/s. The simulation results and test results of ammonia concentration at the measurement points at 0.9 m were compared, as shown in Figure 15. The simulation results showed good agreement with the measurement results, and the relative error was less than 10%.

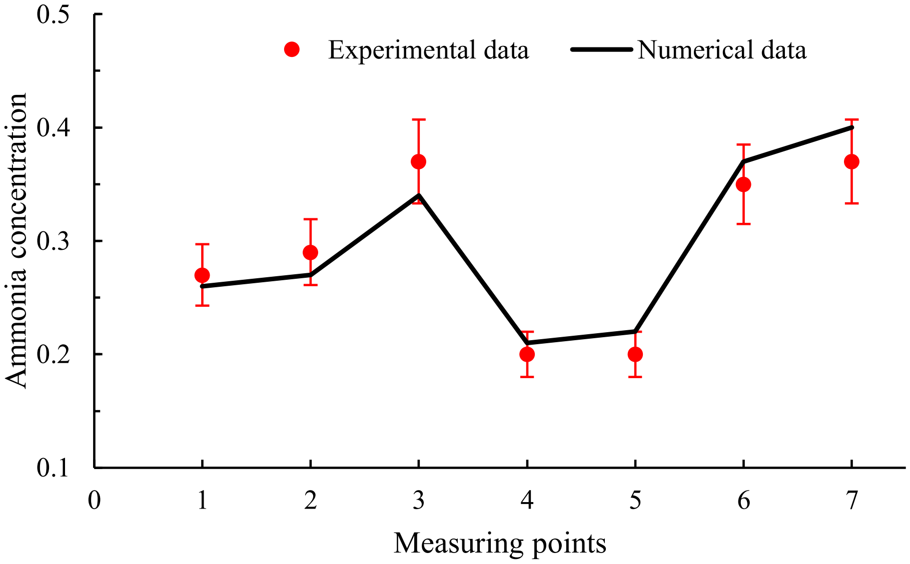


Figure 15. Verification of turbulence models (numerical data and experimental data).

4.2.4. Solution Methodology and Boundary Conditions

The discretization of the temperature, momentum, turbulent kinetic energy, turbulent dissipation rate, and material conservation equations is all done using the first-order scheme. The pressure interpolation scheme is a body-force-weighted scheme. The simulation was conducted at steady state with the energy equation convergence criteria of 1×10^{-6}. The no-slip velocity condition was imposed on the wall; it can be expressed numerically as:

$$\mathbf{u}(\mathbf{x}, t) = \mathbf{u}_s(\mathbf{x}, t) \tag{6}$$

where $\mathbf{u}$ is the fluid velocity field and $\mathbf{u}_s$ is the velocity field at the solid boundary.

In previous studies [48,49], although the size of the exhaust vent and the diffusion concentration of the pollutant are different, the mass diffusion rate of ammonia in a cubicle is within the range of (2~5) $\times 10^{-5}$ g/s. Therefore, the urinal was set as the pollution source in this simulation, and the diffusion rate of the pollutant (ammonia) was set at 5×10^{-5} g/s. In the urinal area, the urinal bucket and the dirt on the lower floor are considered, while in the stool area, the pollution source is directly set at each cubicle.

4.2.5. Ventilation Volume

Figure 16 shows the flow traces in the toilet with upper exhaust outlets. The age of the air is high where the distance from the door is large.

The ventilation volume has an important impact on reducing air pollution in toilets. The ventilation rate required for toilets varies from 5 to 20 ACH in different codes. The mean age of air variation of the toilet under ventilations rates of 5, 10, 15, 20, 25, and 30 ACH was simulated, respectively. The air volume and air velocity of each vent are shown in Table 14.

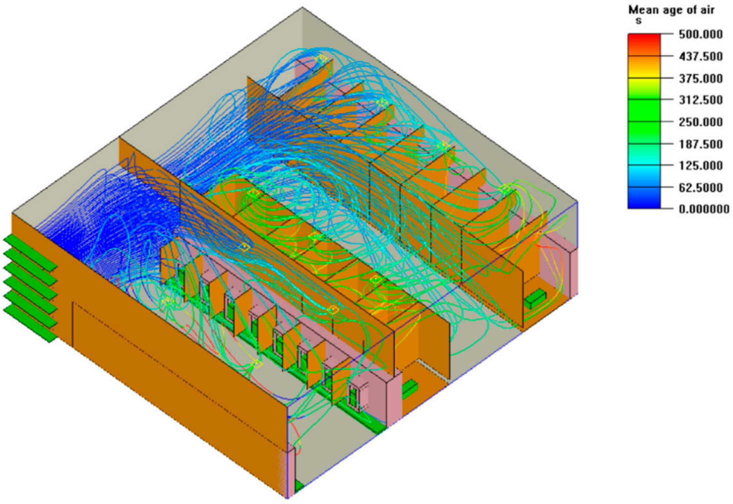


Figure 16. Flow traces in the toilet.

Table 14. Simulated cases.

Ventilation Rate (ACH)	Total Air Volume (m^3/h)	Urinal Area		Stool Area	
		Air Volume (m^3/h)	Air Velocity of Vent (m/s)	Air Volume (m^3/h)	Air Velocity of Vent (m/s)
5	1282	466	0.81	816	0.81
10	2565	932	1.62	1632	1.62
15	3848	1398	2.43	2448	2.43
20	5130	1864	3.24	3264	3.24
25	6413	2330	4.05	4080	4.05
30	7698	2796	4.85	4896	4.86

The mean age of air distribution at a height of 0.9 m is shown in Figure 17. The ventilation efficiency was calculated as shown in Table 15. The simulation result shows that the maximum mean age of the air in the whole toilet and the median mean age of air at different heights gradually decrease with the increase in ventilation rate. Compared with the ventilation rate of 5 ACH, the median mean age of air in the toilet is reduced by 50.2%, 65.7%, 73.6%, 78.4%, and 81.6% when the mean age of the air reaches 10, 15, 20, 25, and 30 ACH, respectively. With the increase in ventilation rate, the ventilation efficiency decreases. Compared with the ventilation efficiency at a ventilation rate of 5 ACH, when the ventilation rate reaches 20 ACH, the ventilation efficiency decreases by 3.14%, and the ventilation efficiency of the area below 1.7 m basically stays below 36%.

Table 15. Ventilation effect of different ventilation rates.

Ventilation Rate (ACH)	Maximum Air Age in Toilet (s)	Median (Average Value in Toilet)		Median (0.9 m)		Median (1.7 m)	
		Mean Age of Air (s)	Ventilation Efficiency	Mean Age of Air (s)	Ventilation Efficiency	Mean Age of Air (s)	Ventilation Efficiency
5	1492	626	57.69%	883	40.77%	860	41.86%
10	801	312	57.51%	459	39.22%	437	41.19%
15	639	215	55.81%	347	34.58%	318	37.74%
20	576	165	54.55%	276	32.61%	252	35.71%
25	522	135	53.33%	228	31.58%	205	35.12%
30	442	115	52.17%	195	30.77%	175	34.29%

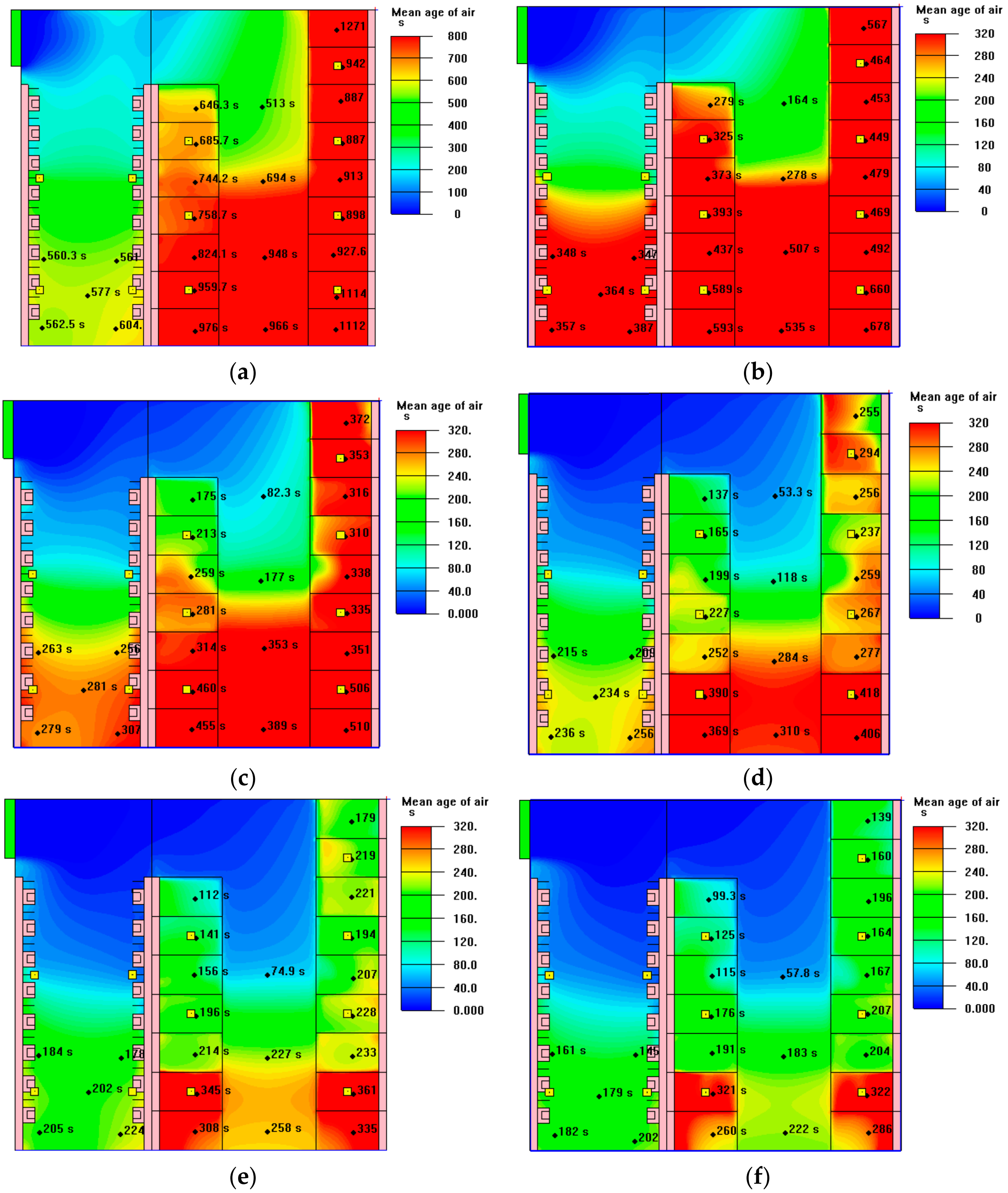


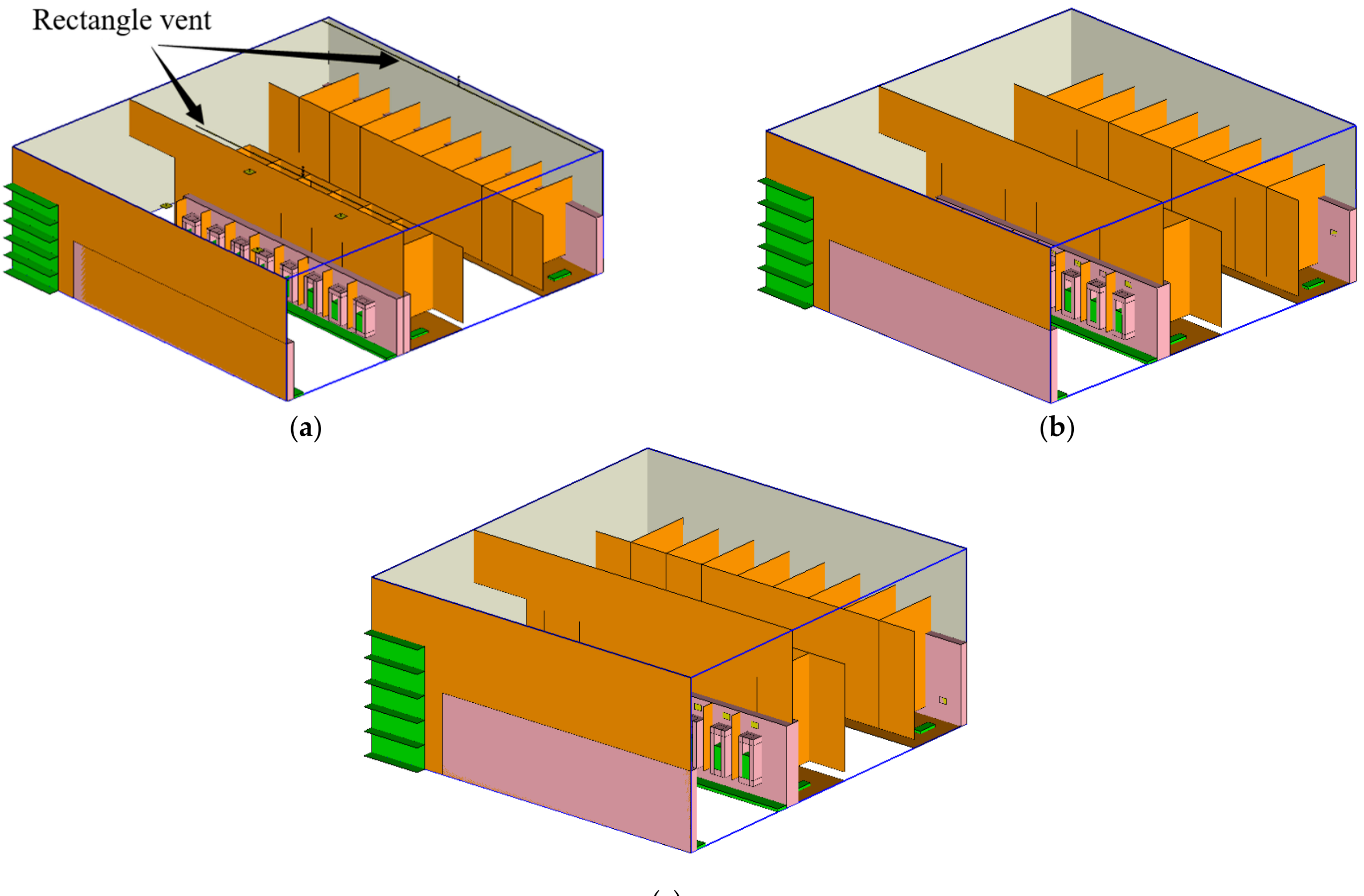
Figure 17. Mean age of air distribution at the height of 0.9 m: (**a**) Ventilation rate of 5 ACH; (**b**) Ventilation rate of 10 ACH; (**c**) Ventilation rate of 15 ACH; (**d**) Ventilation rate of 20 ACH; (**e**) Ventilation rate of 25 ACH; (**f**) Ventilation rate of 30 ACH.

4.2.6. Ventilation System

Based on the top exhaust system of a single-layer shutter, the effects of four layout schemes of an exhaust outlet were analyzed to find the optimal scheme. The boundary conditions for four cases are listed in Table 16, and the models are shown in Figure 18.

Table 16. Boundary conditions.

Cases	Exhaust Vent	Size of Vent (mm × mm)	Number of Vents	Ventilation Rate (ACH)	Air Velocity (m/s)
1	Square vent at the top (Stool area)	200 × 200	7	20	3.24
	Square vent at the top (Urinal area)	200 × 200	4	20	3.24
2	Rectangle vent at the top (Stool area)	7000 × 20; 9000 × 20	2	20	2.83
	Square vent at the top (Urinal area)	200 × 200	4	20	3.24
3	Rectangle vent at the bottom (0.8 m above the ground in stool area)	100 × 200 (0.8 m)	16	20	2.83
	Rectangle vent at the bottom (1.2 m above the ground in urinal area)	100 × 200 (1.2 m)	8	20	3.24
4	Rectangle vent at the bottom (0.3 m above the ground in stool area)	100 × 200 (0.3 m)	16	20	2.83
	Rectangle vent at the bottom (1.2 m above the ground in urinal area)	100 × 200 (1.2 m)	8	20	3.24



(**a**) (**b**) (**c**)

Figure 18. Ventilation models: (**a**) The model of case 2; (**b**) The model of case 3; (**c**) The model of case 4.

According to the simulation results of four cases, the mean age of air and ammonia concentration distribution characteristics of the stool area and urinal area at the heights of 0.9 m and 1.7 m, as well as the whole space, were analyzed. Table 17 shows the statistical results of four cases.

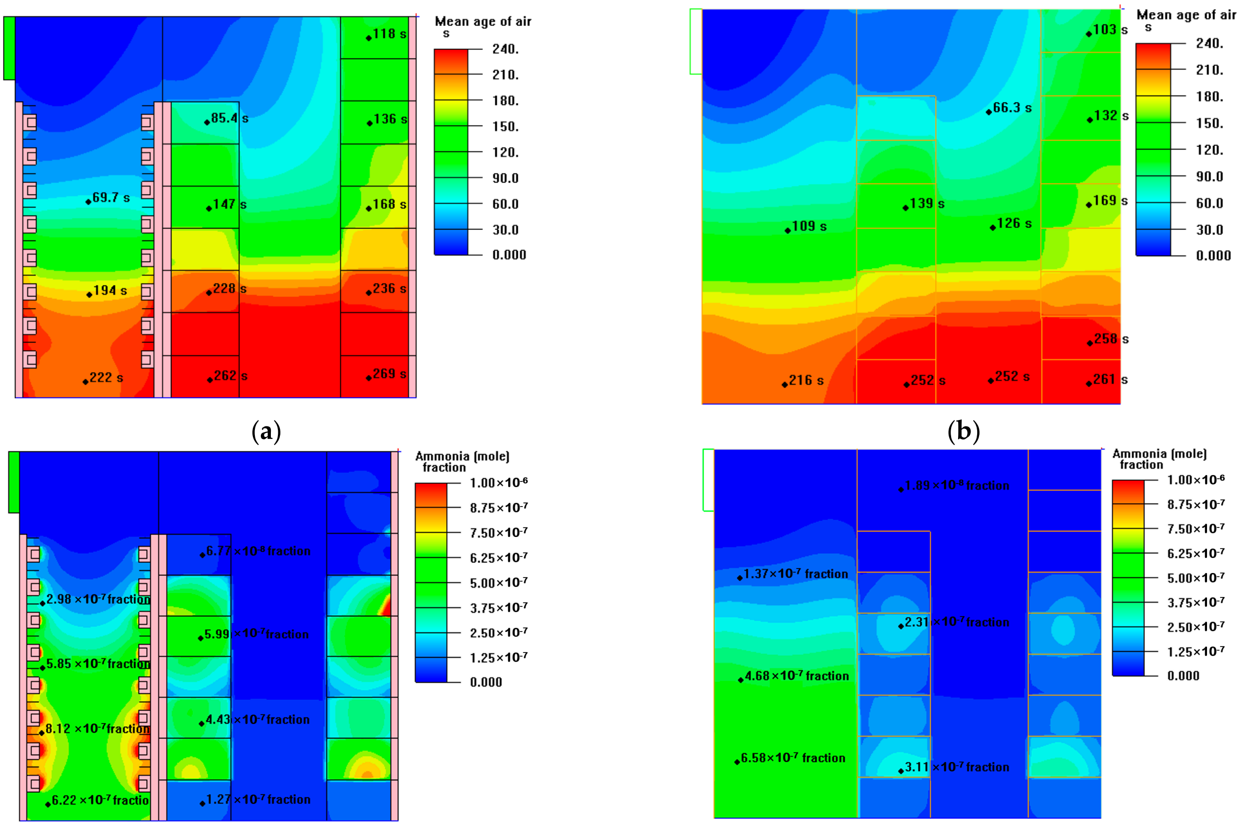
Table 17. Simulation results statistics.

Cases	Median Air Age (s)	Ventilation Efficiency	Ammonia Concentration Distribution (ppm)					Class of Toilet
			Height of Stool Area		Height of Urinal Area		Whole Toilet	
			0.9 m	1.7 m	0.9 m	1.7 m		
1	168	53.57%	1.98	1.45	0.50	0.39	1.11	II
2	156	57.69%	1.45	1.09	0.50	0.39	0.90	II
3	140	64.29%	0.81	0.24	0.47	0.34	0.39	I
4	138	65.22%	0.21	0.10	0.47	0.34	0.26	I

For the top exhaust, compared with case 1, the ventilation efficiency of case 2 (57.69%) is higher, and the overall pollutant concentration of case 2 (0.9 ppm) is lower. So, it is better to set a rectangle vent at the top of stool area.

The ventilation effect of the bottom vent is obviously better than that of the top vent. Cases 3 and 4 both meet the standard of the Class I toilets in Standard GB/T17217-1998 [44]. The ammonia concentration of case 4 is 33.3% lower than that of case 3, so the bottom vent height of 0.3 m is much better in the stool area. In ZJ station and NJ station, the vent heights in the stool area and urinal area are 0.8 m and 1.2 m, respectively. So, the heights of the vents in the stool area are not the most reasonable.

The simulation results of air age and ammonia concentration at 0.9 m and 1.7 m for case 4 are displayed in Figure 19. There is a dead space zone of exhaust in the innermost part of the stool area, so it is recommended to add exhaust outlets at the innermost ceiling of the stool area to enhance the exhaust effect.



(**a**) (**b**)

(**c**) (**d**)

Figure 19. The simulation results of case 4: (**a**) Mean age of air distribution at 0.9 m; (**b**) Mean age of air distribution at 1.7 m; (**c**) Ammonia concentration distribution at 0.9 m; (**d**) Ammonia concentration distribution at 1.7 m.

On the basis of the top exhaust (case 2) system, a fresh air supply system is added in case 5. The fresh air outlet is arranged at the top of the corridor in the stool area, as shown in Figure 20. The ventilation rate is 20 ACH. The size of the fresh air outlet is 400 mm × 400 mm, the fresh air volume is 20% of the exhaust volume, and the corresponding supply air velocity is 0.57 m/s.

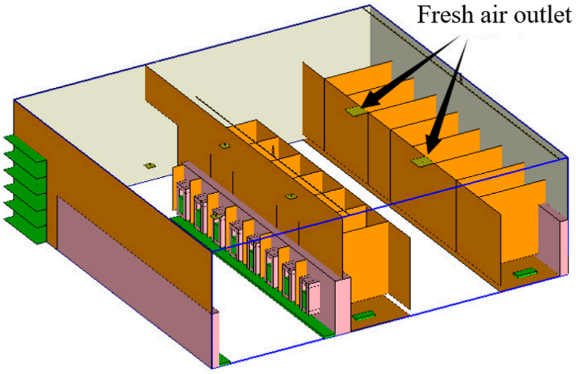


Figure 20. Case 5: The top exhaust and outdoor fresh air system.

In addition, case 6 is to add the air supply system based on the bottom exhaust (case 4) system. The setting of the fresh air inlet in case 6 is the same as in case 5. Three indexes, including the mean age of air, ventilation efficiency, and ammonia concentration, were compared among different cases; Table 18 shows the statistical results of each case. For the top exhaust system and bottom exhaust system, adding a fresh air supply system has an impact on the mean age of air in the toilet, which can improve ventilation efficiency; however, the increase is no more than 5%. The data show that the fresh air system has little effect on ammonia concentration.

Table 18. Statistical results.

Case	**Ventilation**	**Median Mean Age of Air (s)**	**Ventilation Efficiency**	**Ammonia Concentration Distribution (ppm)**					**Class of Toilets**
				Stool Area		**Urinal Area**		**Whole Toilet**	
				0.9 m	**1.7 m**	**0.9 m**	**1.7 m**		
2	Top exhaust	156	57.69%	1.45	1.09	0.50	0.39	0.90	II
4	Bottom exhaust	138	65.22%	0.21	0.10	0.47	0.34	0.26	I
5	Top exhaust + fresh air supply	149	60.40%	1.49	1.04	0.49	0.39	0.89	II
6	Bottom exhaust + fresh air supply	136	66.18%	0.18	0.086	0.48	0.34	0.25	I

4.3. Discussion of the Air Quality Improvement

The research found that the service capacity of public toilets in some stations needs to be improved. A suitable RMFC can reduce the probability of queues for passengers. The main factors affecting RMFC are the maximum hourly service number, RMF, and RSU in male toilets. The recommended SCCH is listed in Table 9.

The RMFC of 1:2 stipulated in Standard TB10100-2018 [43] is not appropriate. The design method for public toilets proposed in Section 4.1.2 has been applied to the design of railway stations. According to the survey, the recommended RMFC is 1:1.33 when RMF is 1:1, and the recommended SCCH for female and male toilets is 12 and 16 when RSU is 1:1.

As the ventilation volume increases, the air quality of toilets improves, but the improvement will be weaker and weaker. An air change rate of 20 ACH is recommended. Among the 22 toilets surveyed, the ventilation rate ranged from 6.0 to 29.0 ACH. Among them, the ventilation rate of 16 toilets was less than 15 ACH, and the ventilation rate of

18 toilets was less than 20 ACH. The ventilation rate of the existing public toilets was not enough. It is necessary to optimize the ventilation system in most toilets.

The ventilation system has a significant impact on the distribution of pollutant concentrations in the toilet. The upper supply and down exhaust are the best for pollutant emissions from mobile public toilets [33]. What is more, forced ceiling supply and wall exhaust systems proved to be the optimal ventilation systems for bathrooms [25]. Previous studies have focused on individual toilets, and there is a lack of research on public restrooms with multiple cubicles. This paper analyzed the effect of different ventilation forms. The results show that the bottom exhaust is obviously better than the upper exhaust, and the recommended height for an exhaust outlet in a stool area is 0.3 m. In order to make the airflow distribution more uniform, the auxiliary upper exhaust outlet can be added in the innermost part of the stool area. What is more, it is unnecessary to set up a fresh air system, which has little effect on the mean age of the air and ammonia concentration.

5. Conclusions

Nowadays, there is a lack of scale, an imbalance in RMFC, and poor air quality in some railway station toilets. In order to provide healthy, comfortable, and convenient toilet services, this paper investigated the air quality and ventilation systems of 22 public toilets in 10 railway stations in China. The pollutant concentration and the service number of toilets were tested. A model of a typical toilet was created by a CFD program to investigate the influence of different ventilation forms and fresh air systems on indoor air quality and to optimize ventilation systems. The conclusions of the study are as follows:

(1) The main pollutant in public toilets is ammonia, which averaged between 0.01 and 2.04 ppm in the toilets tested. Approximately 80% of the surveyed toilets meet the standard of ammonia concentration (0.395 ppm) in Class I toilets, while 20% of toilets with poor ventilation exceed the standard. The ammonia concentration is mainly affected by the service number, ventilation rate, and cleaning frequency.

(2) For toilets with good ventilation, the ammonia concentration decreases with the decrease in service number when service number is less than 100 people/(cubicle · day). As service number increases, the influence of service number becomes smaller, and the maximum ammonia concentration is mainly affected by ventilation rate and cleaning frequency. In 20% of public toilets, the change in ammonia concentration was delayed by about 1 to 2 h with the change of hourly service number.

(3) The public toilets at large and medium stations generally appear to have queues during peak hours. The recommended SCCH for female toilets is 12. The SCCH of male toilets is related to the RSU, which is suggested to be 1:1~1:0.8, and the corresponding SCCH is 16~20.

(4) The method for calculating the number of toilet cubicles was proposed, and the optimal RMFC with different RSUs was investigated. This design is more suitable for public toilets at railway stations, which can effectively prevent queuing.

(5) Eighty percent of toilets use the top exhaust system, and twenty percent of toilets use the up-supply and down-return systems. The ventilation rates for the 22 surveyed toilets are between 6.0 and 29 ACH. The recommended ventilation rate for a toilet is 20 ACH. There are 18 toilets with ventilation rates below 20 ACH. The increase in ventilation rate can effectively improve the indoor air quality of toilets.

(6) The bottom exhaust system is better than the upper exhaust. It is suggested to set the bottom exhaust outlet in the stool area at 0.3 m and to add auxiliary upper exhaust outlets in the innermost part of the toilet. The fresh air system basically has no influence on the ammonia concentration.

This study reflects the current situation of public toilets in railway stations, proposes a design regarding the number of toilet cubicles for stations of different sizes, and provides a reference for the design of public toilets and the revision of the existing standard. The design for toilets in different stations should be combined with the actual peak hour departure quantum. For existing stations, attention should be paid to the queuing situation and sanitary conditions of the toilets to improve the comfort of travelers. It is of great significance to practical engineering, greatly improving the comfort of passengers and promoting the level of civilization in the city. The limitations of this paper are that only high-speed railroad stations were investigated, which are all located in hot-summer and cold-winter zones, and that only ammonia concentrations in restrooms were tested without considering other pollutants. In the future, the air quality of toilets in other public places (such as airports and general stations) or railway stations in other climatic zones can be investigated.

Author Contributions: Conceptualization, J.Y. and C.Q.; methodology, J.Y. and J.Z.; software, J.Z. and J.T.; validation, J.Y., C.Q. and K.L.; formal analysis, J.Y. and C.Q.; investigation, J.Y., C.Q., J.Z., J.T. and K.L.; resources, J.Y. and X.X.; data curation, C.Q., J.Z. and K.L.; writing—original draft preparation, J.Y., C.Q. and J.Z.; writing—review and editing, J.Y. and C.Q.; supervision, J.Y. and X.X.; project administration, J.Y. and X.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank all persons who helped collect data.

Conflicts of Interest: The authors declare no conflict of interest.

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