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Influencing Factors and Purification Performance of a Negative Ion Air Purifier for Indoor Ammonia Gas Removal

Yilin Li [1,2,*], Zewen Liu [1], Yidong Li [1], Ying Chen [3], Ziding Bai [4], Huaiwang Jing [1], Ruiyan Zhang [1] and Jianbo Chen [1,*]

[1] School of Environment and Architecture, University of Shanghai for Science and Technology, Shanghai 200093, China
[2] Jiangsu Province Engineering Research Centre of Construction Carbon Neutral Technology, Suzhou University of Science and Technology, Suzhou 215011, China
[3] Dong Yuan Group, Shanghai 200093, China
[4] Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
* Correspondence: yilin.li@usst.edu.cn (Y.L.); cjbzh@usst.edu.cn (J.C.)

Abstract: The negative ion air purifier (NIAP) has been used for capturing particulate matter. Nevertheless, the knowledge on its effectiveness in removing other air pollutants such as ammonia gas remains limited. In this study, the effect of an NIAP for indoor ammonia gas removal was evaluated through a series of experimental studies. The applicability and different influencing, operating, and environmental factors on the ammonia gas removal performance were firstly investigated by conducting a series of experiments. Then, in order to understand the performance of the NIAP and the spatial distribution of ammonia gas and other by-products, indoor field measurements of ammonia gas, ozone, and negative ion concentrations in a real bathroom were performed for different cases with the NIAP turned on and off. The results indicated that negative ions were effective in reducing ammonia gas concentration. The operating and environmental factors including upstream wind speed, degree of operating voltage, and initial ammonia gas concentration have great influences on the ammonia gas removal efficiency of the NIAP. The highest removal efficiency can reach to 95.8%, when the upstream wind speed was 0.8 m/s and the degree of operating voltage was at gear 3 (3.0 kV). The purification efficiency of ammonia gas for the NIAP could reach up to 80%.

Keywords: negative ion air purifier; ammonia removal; indoor environment; experimental study

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1. Introduction

People spend approximately 90% of their time indoors; hence, indoor air pollution constantly threatens occupants' well-being if it exceeds the maximum thresholds [1]. However, with an increasing number of highly sealed buildings around the world, the lack of adequate ventilation would cause low indoor air quality [2,3]. Among different rooms, the bathroom can significantly influence the air quality of adjacent indoor space and has a larger impact on people's health [4]. Although bathrooms usually have mechanical ventilation systems and sometimes openable windows, the environment can still be heavily contaminated with different pollutant such as PAHs, SxOx and NxOx [5], VOCs [6], ammonia gas, and odors [7–10], which are difficult to be eliminated completely. As one of the main gaseous pollutants in the bathroom, ammonia gas is an alkaline substance with a very

strong, pungent odor [11]. It can saponify human tissue, denature protein, damage the nervous system and even cause metabolic disorders, and have a strong destructive effect on the cell membrane in human bodies [12]. The pungent smell of ammonia would sting people's noses and hurt their breathing systems when the indoor ammonia gas concentration exceeds 0.20 mg/m^3 [13]. However, it is difficult to remove ammonia in a bathroom and decrease its concentration level to meet the indoor air quality standards due to a lack of ventilation or proper removal approach, especially in the corners of the bathroom [14].

The commonly used air purification methods include applying air filtration devices, using absorption material, the photocatalysis oxidation method, plasma purification technology, etc., as presented in Table 1 [15]. Air filtration is one of the simplest and widely used methods, where the suspended particles get captured in the filter or get collected by the generated ion [16]. HEPA filters are often used to remove particulate matter and bioaerosols of 0.3 microns or larger sizes [17–19]. However, HEPA filters need to be replaced regularly which cause maintenance troubles and extra expenses [20], while the NIAP does not require replace devices, thus reducing the extra expenses [21]. Methods with absorption materials are thought to be effective for removing indoor VOCs and PM2.5 [22]. Among them, activated carbon-based filters are usually used to remove common pollutants such as VOCs from indoor air [23]. Activated carbon has a stronger absorption capacity for non-polar substances compared to polar substances, and thus it is not suitable for removing high concentrations of gas [24], while NIAP can effectively remove high concentrations of gas [25]. In addition, absorbent needs to be periodically replaced to maintain the effectiveness of this technology [26]. Ren et al. proved that the activated carbon can improve ammonia absorption efficiency but can only be applied in low-temperature occasions [27]. The photocatalytic oxidation technology is one of the most effective methods to eliminate indoor air pollutants including indoor viruses [28] and VOCs [29]. In the last decades, ultraviolet photocatalytic oxidation technology has received much attention [30,31]. Present photocatalytic technology is only suitable for small air volumes, and thus its application in large space is limited [32]. In terms of light irradiation methods, the use of far-ultraviolet light and negative ionizers are effective in inactivating bioaerosols [33], while infrared irradiation of silver-plated TiO_2 catalysts photo-catalytically can be used for removing gaseous phenol [34]. Plasma purification technology has proved to be effective in absorbing ammonia [35] but may cause secondary pollution such as O_3 and NO_X [36]. NIAP can reduce the concentration of ozone, which minimizes secondary pollution [37].

Table 1. Indoor pollutant removal methods.

Methods	Pollutant	Principle	Limits
Air filtration	TVOC [16]; PM2.5 [17–19]; indoor virus [20];	Suspended particles get captured in the filter	Secondary source of pollution
Adsorption materials	formaldehyde, PM2.5 [21]; VOCs [22,24]; acetaldehyde and toluene [23]	MOFs have ultra-high adsorption properties	Periodically replaced
Photocatalytic oxidation	Ammonia [25]; viruses [26]; VOCs [27]; formaldehyde [28–30] Bioaerosols [31]; gaseous phenol [32]	IAPS are oxidized by PCO; micro-organisms are damaged by VOCs	Low photocatalytic activity
Plasma purification	Ammonia [33]	Dielectric barrier discharge	Secondary pollution [34]

In recent years, the application of NIAPs is on the rise due to its advantages such as energy-saving potential, lower noise level, and comparably lower maintenance costs [38,39]. The negative ions have proved to be able to effectively reduce the concentrations of in-

halable particles, suspended bacteria, and VOCs [40]. Grinshpun et al. [25] conducted experiments on different types of NIAPs and found that the purification performance of NIAPs for inhalable particles is satisfactory. They also revealed that NIAPs have better purification performance for respirable particles and can effectively reduce the ammonia concentration with suitable wind speed. Jiao and Sun [41] applied an NIAP in a poultry house and observed that the total number of aerobic bacteria in the house was decreased by more than 60% after turning on the NIAP for 4.5 h. Luo et al. [42] found that the NIAP can reduce the concentration of house dust mites and improve the symptoms of allergic asthma. Gao et al. [43] revealed that compared with the traditional ventilation method, the negative ion air purification system led to a higher economic net value and shorter investment cycle. Guo et al. [37] found that the NIAP can not only improve the efficiency of air purification but also solve the problem of increased ozone which may cause secondary pollution. However, NIAPs may generate large amounts of negative ions which may be harmful to human health [44]. Many researchers also put great efforts in studying the influencing factors of negative ions in removing air pollutants. Ye and Kang et al. [45] found that the increase in particle size reduces the efficiency of the NIAP, while the airflow velocity has a synergistic effect on the filter of the purifier. Li et al. [46] revealed that the indoor temperature and humidity can greatly influence the concentration of negative ions, while the wind velocity and direction have major impacts on the diffusion distance and concentration of negative ions. Wang et al. [47] showed that the efficiency of the NIAP in removing PM2.5 firstly rises and then decreases with the increase in humidity. Ren [48] found that the increase in output voltage of the purifier can result in lower wind velocity and higher efficiency of negative ion purification.

Based on the above literature analysis, although the negative ion has proved to be effective in improving the indoor air environment, there is a lack of research information on the NIAP for removing ammonia in the indoor environment. In addition, the operating and environmental influencing factors of the effectiveness of the NIAP in ammonia gas removal need to be investigated for achieving optimal performance. The concentration levels of by-products produced by the NIAP such as ozone have not been discussed thoroughly in previous studies. To this end, this study aims at investigating the performance of the NIAP for removing ammonia gas in the indoor environment. The influencing factors including upstream wind speed, initial concentration of ammonia gas, and degree of voltage on the performance of the NIAP were studied through a series of experiments. Field measurements on concentrations of ammonia gas, ozone, and negative ions were performed in a bathroom with a prototype of the NIAP in order to understand the spatial distribution of the ammonia gas and other by-products. The ammonia gas removal efficiency of the negative ion air purifier in a bathroom was also calculated.

2. Materials and Methods

2.1. Mechanism of Negative Ion Air Purification

As shown in Figure 1, the negative ion air generator consists of the power supply, buck rectifier filter, voltage regulator, oscillator amplifier, high-frequency transformer rectifier, and emitter plate. The buck rectifier filter and voltage regulator first convert the AC power supply to DC power and stabilize the operating voltage to a required degree. The operating voltage is then amplified by an oscillator and a high-frequency transformer rectifier to form an uneven electric field, which generates negative ions. As the high DC voltage on the two electrodes is loaded, it forms an ionization field where the negative polarity corona accumulates at the tip to form a space charge. When the electrons in the corona are ionized, positive ions accumulate on the surface of the pole plate and the electrons are dispersed. When the strength of the space electric field exceeds the strength of the ionization field,

non-self-sustaining discharge occurs. This leads to a continuous intensified ionization process and results in corona discharge. The generated negative ion finally reaches to the emitter plate and would be used for air purification.

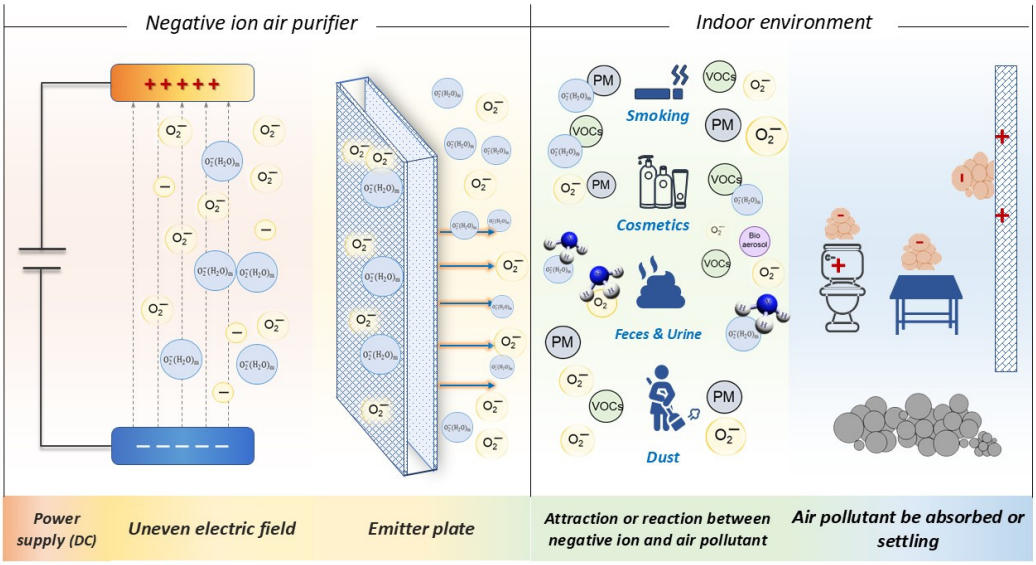


Figure 1. Mechanism of negative ion air purification.

Negative ion purifiers produce a large number of negative ions and a small amount of ozone during the discharge process. During the purification process, negative ions and ozone can be generated which may cause health issue if their concentrations are beyond the limited values. Therefore, the concentrations of negative ions, ammonia, and ozone should be monitored and investigated during the experiments in order to gain a comprehensive understanding of the ammonia removal effect of negative ion air purification. The gas ionization process can be described by the Penning effect [49].

$$\mathrm{M}^* + \mathrm{A} \rightarrow \mathrm{A}^+ + \mathrm{M} + \mathrm{e} \quad (1)$$

$$\mathrm{M}^* + A_2 \rightarrow 2\mathrm{A} + \mathrm{M} \quad (2)$$

The gas molecules entering the NIAP react to become high negative ion concentrations, which further actively capture airborne particles (ammonia, formaldehyde, etc.), thus reducing the concentration of ammonia in the room. In the meantime, the ozone generated from the oxygen and oxygen atoms in the air also reacts with the ammonia. The reaction process can be expressed as follows:

$$\mathrm{e}^* + O_2 \rightarrow 2\mathrm{O} + \mathrm{e} \quad (3)$$

$$O + O_2 \rightarrow O_3 \quad (4)$$

$$O_3 + NH_x \rightarrow NH_x + H_2O \quad (5)$$

$$\mathrm{e}^* + NH_3 \rightarrow NH_2 + \mathrm{e} + \mathrm{H} \quad (6)$$

$$O + NH_3 \rightarrow NH_2 + OH \quad (7)$$

2.2. Experiments on NIAP Device

In order to evaluate the performance and influencing factors of the negative ion generator, an experimental test facility was set up as shown in Figure 2. A high-pressure cylinder with a valve was used as the ammonia gas generator. Figure 3 shows the instruments for the experiments, including the NIAP device, an ammonia analyzer, and an ozone detector. The geometric dimension of the NIAP device was 450 mm × 550 mm × 300 mm, and the

operating voltage can be adjusted among four gears (gear 1: 2 kV, gear 2: 2.5 kV, gear 3: 3 kV, gear 4: 3.5 kV). The operating voltages tested were used to confirm the appropriate voltage range for the NIAP in field measurements. The NIAP device was installed between the upstream and downstream sample collection spots.

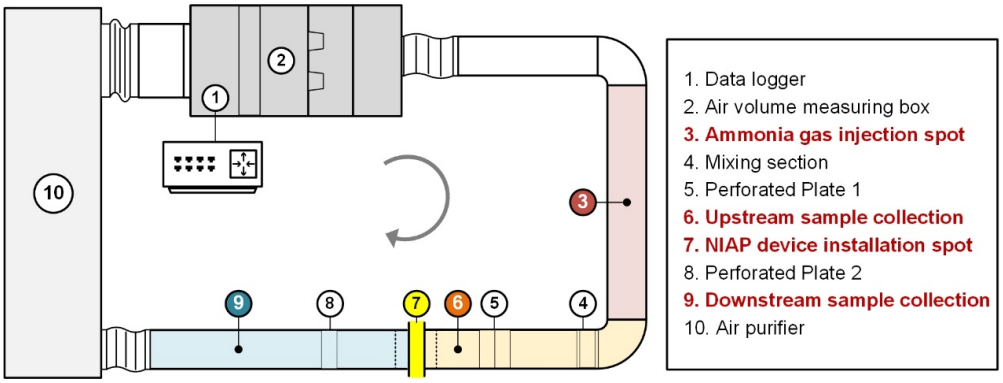
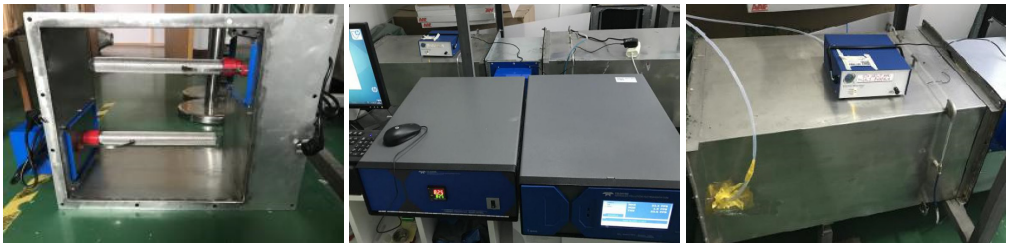


Figure 2. Schematic diagram of experimental test facility set-ups.



NIAP device Ammonia analyzer Ozone detector

Figure 3. Instruments for experiments.

During each experiment, the NIAP was firstly turned on and its voltage was adjusted to a certain degree. The upstream wind speed was set up by the air volume measuring box to the working condition. When the upstream wind speed is stable, ammonia gas was injected into the air duct at the injection spot. Then, the ammonia gas was fully mixed with air through the mixing section and perforated plate 1. The initial ammonia gas concentration of the mixed air was measured at the upstream sample collection spot N_2. After the mixed air passed through the NIAP device, the ammonia gas concentration of the purified air was measured at the downstream sample collection spot N_1. At last, the purified air returned to an air purifier unit, and the residual ammonia gas was totally purified through chemical adsorption and filtration.

The operating voltage determines the efficiency of negative ion production, which influences the removal efficiency of ammonia. The wind speed affects the air flow, which affects the dispersion of pollutants and the capture efficiency of pollutants by the purifier. In the experimental study, the different concentrations of ammonia relate to the ability of the purified ammonia concentration to meet national standards, which cannot be ignored in the study, so we decided to use these three parameters as influencing factors. In order to identify the influencing factors of ammonia gas removal efficiency and optimal working conditions of the NIAP, the experiments were divided into five groups with different initial ammonia gas concentration. For each group, various upstream wind speeds and four degrees of operating voltage of the NIAP were tested. The test conditions are demonstrated in Figure 4. In order to achieve reliable results, the ammonia analyzer was warmed up for 40 min before formal measurement. Each experiment takes five consecutive readings of stable values, and their average values were calculated. The error of the ammonia

concentration of each sample was less than 1% of the set value. The purification efficiency of the NIAP in removing ammonia gas was calculated by using Equation (8).

$$\eta = \left(\frac{N_1 - N_2}{N_1}\right) \tag{8}$$

where N_1 represents the upstream ammonia gas concentration, mg/m^3; N_2 represents the downstream ammonia gas concentration, mg/m^3.

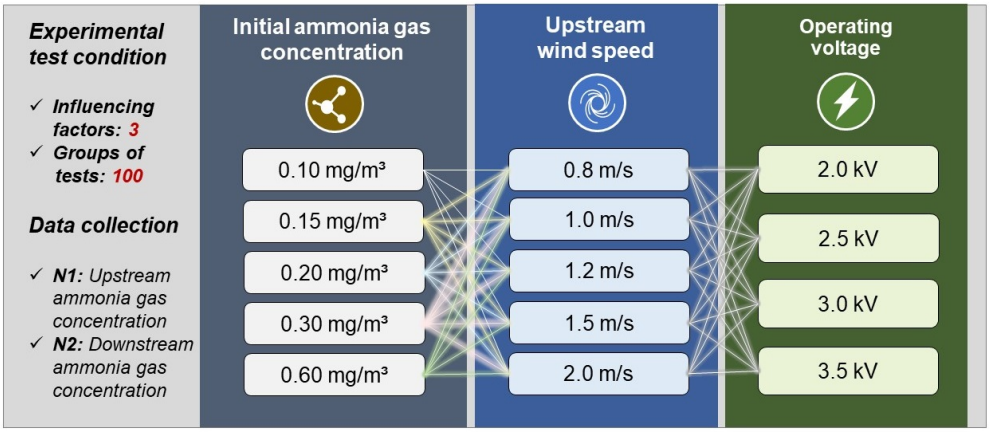
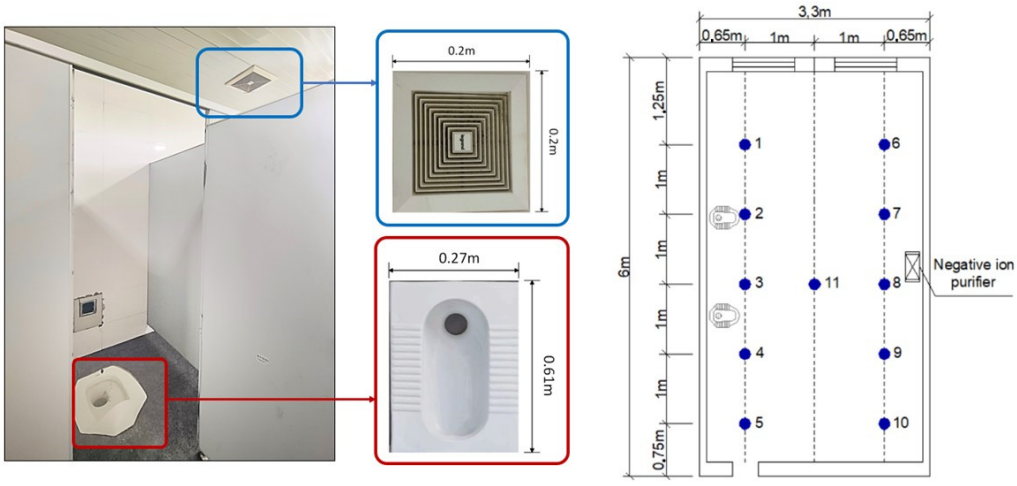


Figure 4. Experimental test conditions.

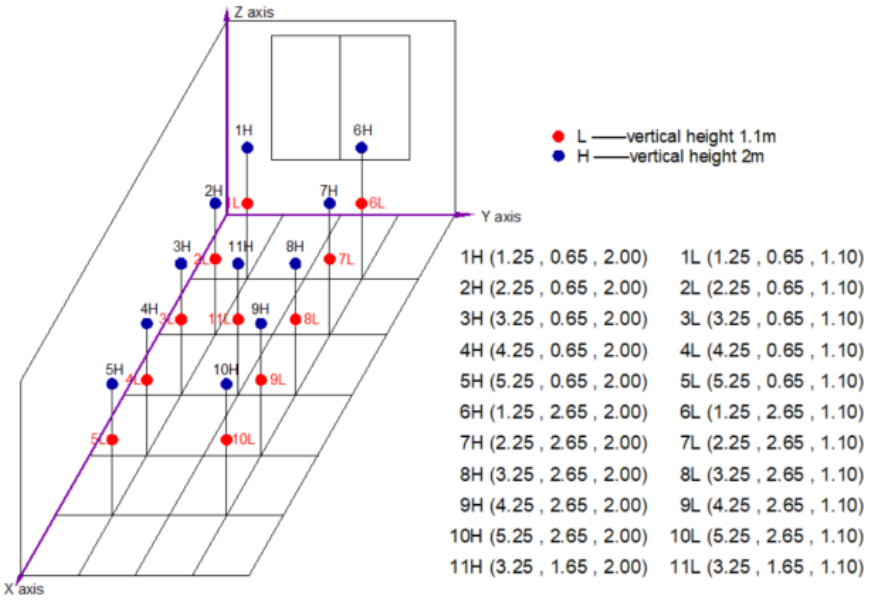
2.3. Field Measurements of the NIAP

Field measurements on a selected negative ion air purifier were conducted in a real bathroom in an office building located in University of Shanghai for Science and Technology. As shown in Figure 5a, the bathroom (width: 3.3 m, length: 6 m, height: 2 m) has two urinals 0.5 m away from the west wall, and an exhaust vent on the roof. A commercially available product German BIO NIAP (as shown in Table 2) was applied, which was suitable for the floor area of the bathroom. As shown in Figure 6, the experimental test instruments include the ammonia analyzer, ozone analyzer, anemometer, and ion concentration detector. Specifications of all the sensors and instruments are presented in Table 3. During the experiment, potential sources of errors may include the airtightness of the instruments or failure to calibrate experimental equipment prior to the experiment. In this experiment, all instruments and equipment were inspected and calibrated before the commencement to ensure the reliability of the experimental data.



(**a**)

Figure 5. *Cont.*

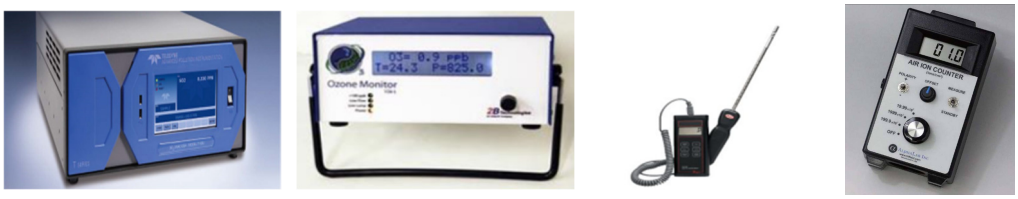


(**b**)

Figure 5. Locations of detection points. (**a**) The bathroom for field measurements. (**b**) Perspective view.

Table 2. Technical specification of German BIO negative ion air purifier.

Parameters	Value
Dimensions (mm)	380 × 370 × 91
Gears of operating voltage	Gear 1: 2.2 kV Gear 2: 2.8 kV Gear 3: 3.4 kV
Input voltage (V)	220
Area of efficacy (m^3)	120
Power (W)	20



Teledyne API T201 ammonia analyzer | ECO UV100 ozone analyzer | SWEMA AIR300 anemometer | ALP AIC300 ion concentration detector

Figure 6. Instruments for data collection.

Figure 5b illustrates the arrangement of the measuring spots based on the Chinese national standards [50,51]. For a room with an area of less than 50 m^2, one measuring spot is essential to acquire the pollutant concentration level. The measuring spot should be away from the ventilation vents, 0.5 m away from the surrounding walls, and 0.5~1.5 m height from the ground. Therefore, spot 11L in the central position of the bathroom was chosen to represent the general pollutant concentration level. In order to obtain the distribution of ammonia gas and other pollutants, 21 measuring spots were selected at 1.1 m height (1L~11L) and 2 m (1H~11H) height. The time interval between each two measurements for one experiment was one minute, according to the Chinese national standard GB/T 18883-2022 [50].

Table 3. Specification of instruments.

Instrument	Manufacturer	Range	Resolution	Accuracy	Environmental Condition
Teledyne API T201 ammonia analyzer	Teledyne API, San Diego, CA, USA	0~0.05 ppm, 0~2 ppm	0.001 ppm	0.5%	10–30 °C
ECO UV100 ozone analyzer	ECO Sensors, Newark, CA, USA	0~1 ppm, 0~10 ppm, 0.1~999 ppm	0.01 ppm	2%	/
SWEMA AIR300 anemometer	SWEMA, Farsta, Sweden	0.1–30 m/s	0.05 m/s	5%	−20 to 80 °C
ALP AIC300 ion concentration detector	ALPHALAB Inc., Salt Lake City, UT, USA	1000–1.99^{108} cm^3	10 cm^3	25%	−20 to 60 °C

Two phases of experiments were carried out for different purposes. In order to identify the ammonia gas concentration level in the bathroom, the phase I experiment was conducted from 9:00 am to 18:00 pm every hour during 1~7 October 2018. The ammonia concentration data were collected at measuring spot 11L. Phase II experiments (carried out on 8 October 2018) aimed to obtain and compare the distributions of ammonia gas, ozone, and negative ions with the NIAP off and on. When the NIAP was off, the exhaust fan was kept working to obtain the actual ammonia gas concentration as usual. The fan was turned off, and all the doors and windows were closed and sealed for at least one hour before and during the experiments with the NIAP on. The airflow data, ammonia gas concentration data, and ozone concentration data were recorded at each measuring spot when the experimental conditions were stable. All experiments were repeated independently.

During the field measurements, the ambient temperature was 24 °C and the outdoor relative humidity was 58%, while the indoor temperature was 26 °C and the indoor relative humidity was 62%.

3. Results and Discussion

3.1. Influencing Factors on the Ammonia Gas Removal Efficiency of NIAP

Figure 7 shows the correlations of different influencing factors (including upstream wind speed and degree of operating voltage) on the ammonia gas removal efficiency of the NIAP under various original ammonia gas concentrations. With the same initial ammonia gas concentration and upstream wind speed, the ammonia gas removal efficiency of the NIAP first increased when the degree of operating voltage rose from 2.0 kV to 2.5 kV. However, when the operating voltage exceeded 3.0 kV, the ammonia gas removal efficiency of the NIAP dropped with the increase in the operating voltage. The variation trend is due to that with a higher degree of operating voltage and stronger intensity of the electric field, the frequency of collisions between the ammonia molecules and negative ions increased. However, when the operating voltage between the two electrode plates continues to rise beyond the corona discharge voltage, the electric field will break through the gap between the electrode plates and form a channel; when the voltage between the electrodes exhibits a sharp decline, the purification efficiency is reduced.

With the same initial ammonia gas concentration and degree of operating voltage, the efficiency of the NIAP in removing ammonia gas was increased with a lower upstream wind speed. This is mainly because that higher wind speed may result in a low probability of collisions between the negative ions and the pollutant gaseous molecules. Thus, a smaller amount of ammonia gas may be captured by the NIAP device when the ammonia gas passed by, which eventually results in a higher concentration of ammonia gas downstream.

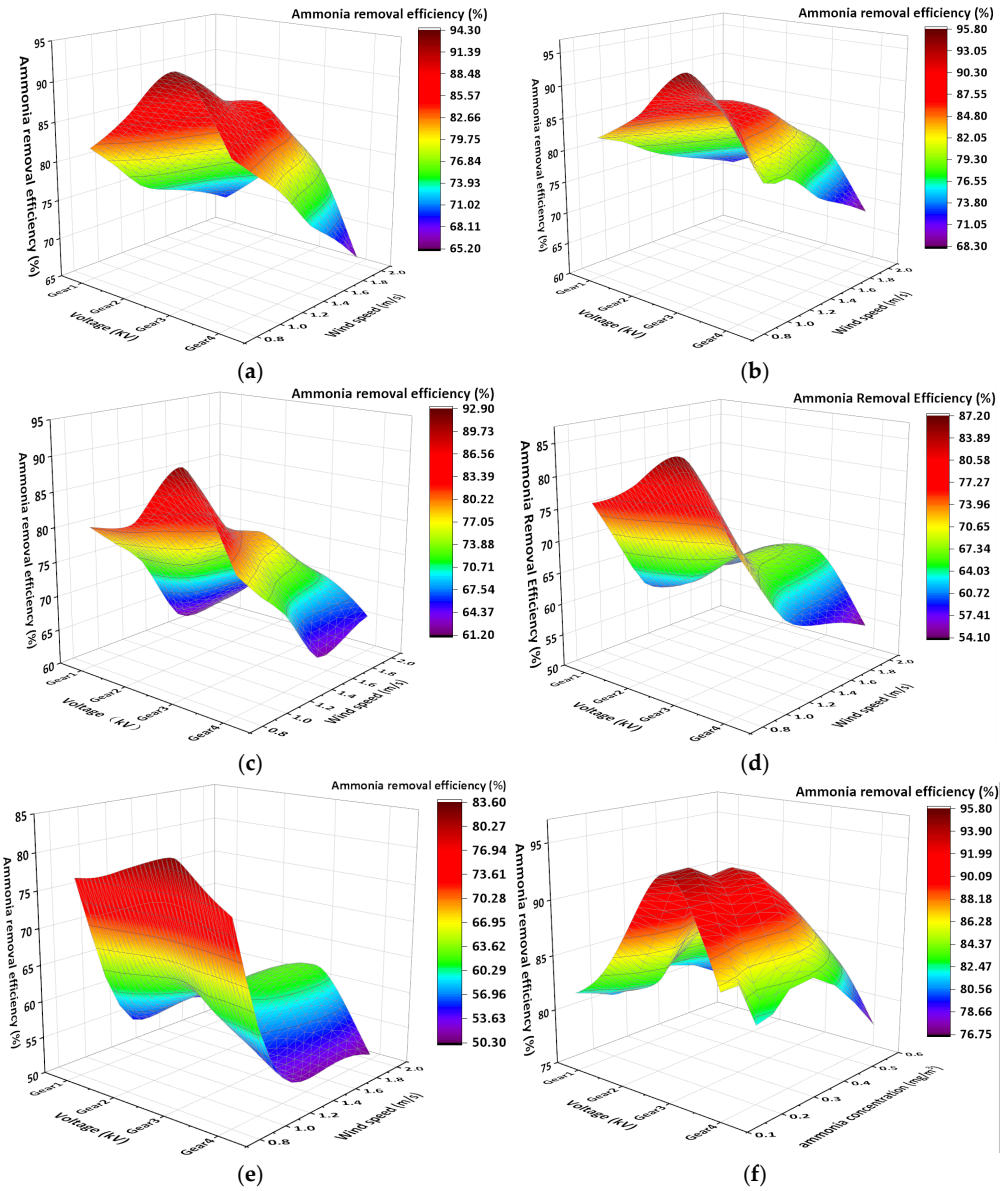


Figure 7. Correlations of different influencing factors on ammonia removal efficiency of NIAP. (**a**) Initial ammonia concentration (0.1 mg/m^3). (**b**) Initial ammonia concentration (0.15 mg/m^3). (**c**) Initial ammonia concentration (0.2 mg/m^3). (**d**) Initial ammonia concentration (0.3 mg/m^3). (**e**) Initial ammonia concentration (0.6 mg/m^3). (**f**) Upstream wind speed (0.8 m/s).

As Figure 7f indicates, under an upstream wind speed 0.8 m/s, the efficiency of the NIAP first increased and then decreased as the initial ammonia gas concentration rose. When the initial ammonia gas concentration was 0.1 mg/m^3, the efficiency of the NIAP was 81.9%, 87.3%, 94.3%, and 84.5% with different gears of operating voltage, gear 1, gear 2, gear 3, and gear 4, respectively. When the initial ammonia gas concentration was 0.15 mg/m^3, the efficiency of the NIAP was 82.10%, 86.70%, 95.80%, and 89.30%, with different gears of operating voltage, gear 1, gear 2, gear 3, and gear 4, respectively. When the initial ammonia gas concentration increased to 0.6 mg/m^3, the efficiency of the NIAP was 77.9%, 79.4%, 83.6%, and 76.8%, which was obviously lower than that with a smaller initial ammonia gas concentration. Therefore, the efficiency of the NIAP first increased and then decreased with a lower initial ammonia gas concentration. When the ammonia gas concentration increased and exceeded the threshold of the national standard of 0.20 mg/m^3, the NIAP was not able to trap all the pollutant molecules, and the efficiency of the purifier gradually decreased.

Based on the analysis of the chamber experiments' results, the highest removal efficiency can reach to 95.8%, when the upstream wind speed was 0.8 m/s and the degree of operating voltage was at gear 3 (3.0 kV). Therefore, the operating voltage was set up at the third gear and the airflow velocity was set up to 0.8 m/s during the field measurements.

Polynomial fitting, based on the principle of least squares [52], determines coefficients by minimizing the sum of squared residuals and has a wide range of applications in data analysis, image processing, and other fields. For high-order polynomials, it will affect the accuracy of the fitting results. However, the fitting results in this experiment are of a second-order polynomial, so it does not affect the fitting accuracy [53]. In addition, linear regression or local regression methods can be used, which are suitable for handling situations where data exhibit approximately linear relationships.

In order to further identify the relationships between the purification efficiency of the NIAP and various influencing factors (the operating voltage, upstream wind speed, and initial ammonia gas concentration), a polynomial fitting equation for the purification efficiency under different conditions was derived, as Equation (9) indicates. In Figure 8, the experimental results and the calculated results are compared, demonstrating good agreement, which indicates the established polynomial equation can be applied to represent the ammonia gas purification process in the experiment. The regression coefficient of the equation was 0.91, indicating that the regression relationship between the influencing factors and the purification efficiency was significant.

$$Y = 93.20229 - 0.95068X_1X_2 - 5.66320X_1X_3 - 17.4402X_2X_3 + 22.9005X_1 - 47.16490X_2 - 3.9659{X_1}^2 + 14.4424{X_2}^2 \quad (9)$$

where X_1 represents the operating voltage, KV; X_2 represents the upstream wind speed, m/s; and X_3 represents the initial ammonia concentration, mg/m^3.

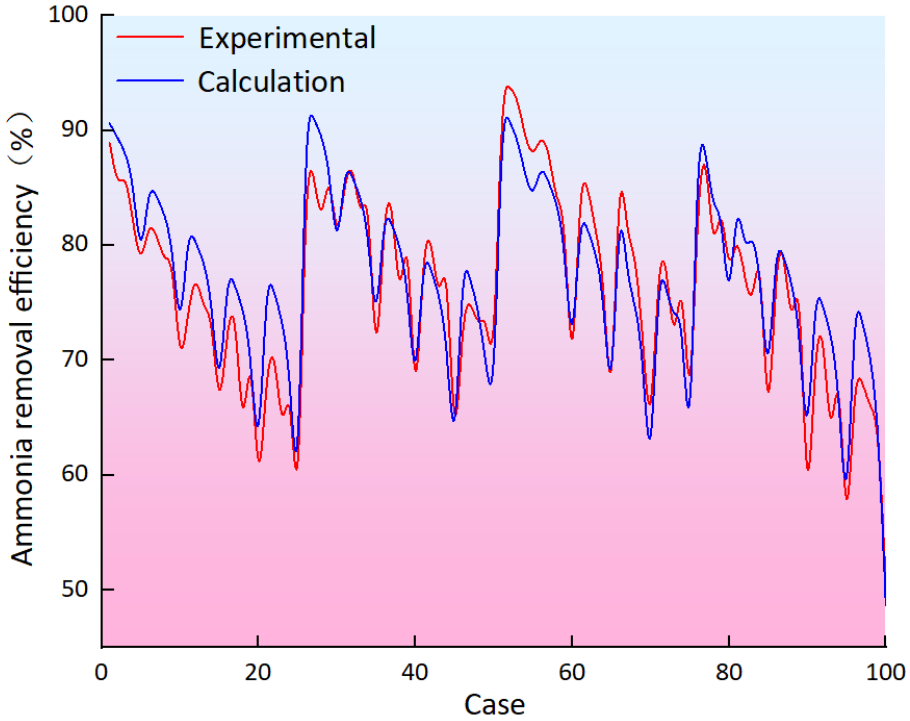


Figure 8. Comparison of experimental and calculated results.

3.2. Results of Field Measurements

3.2.1. Background Concentration Level of Indoor Ammonia Gas

Figure 9 presents the hourly variations in ammonia gas concentrations in the bathroom on 1~7 October 2018, which provides information on the background concentration of

ammonia gas. The results show that the ammonia gas concentration was within the range of 257.3~345.8 ppb. Except for on 5 October, the background ammonia gas concentration values always exceeded the threshold value of an indoor ammonia concentration of 263 ppb in the Chinese national standard GB/T18883-2022 [54]. The maximum ammonia gas concentration occurred on 7 October, reaching 445.1 ppb, which doubled the threshold of the national standard. The results revealed the great necessity of applying methods to remove ammonia gas in the bathroom.

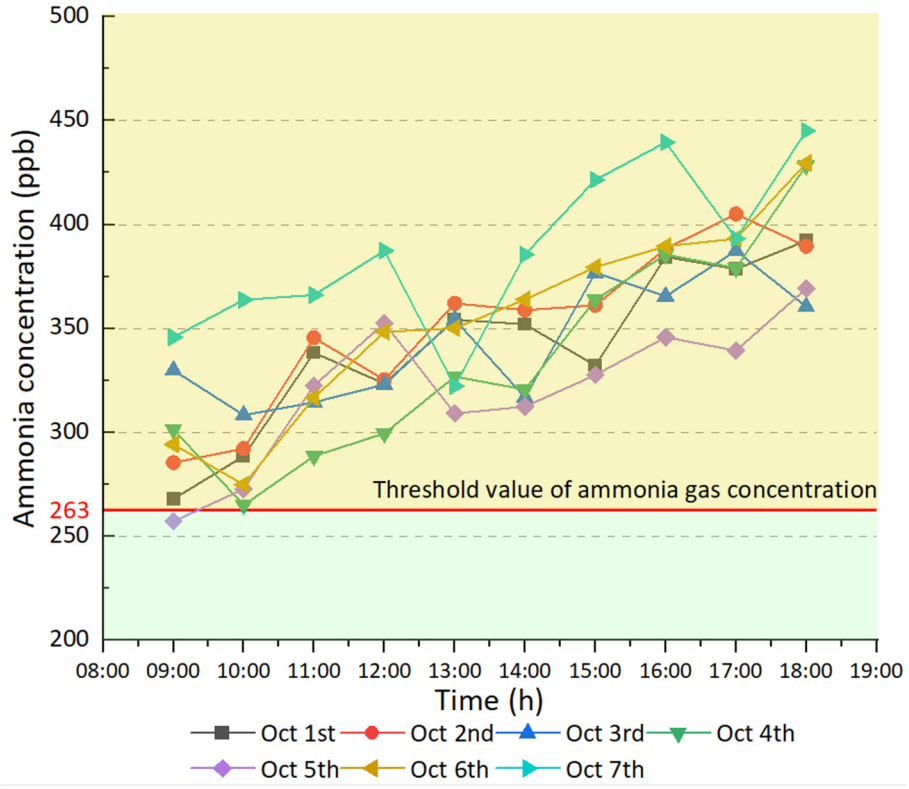


Figure 9. Hourly variation in ammonia gas concentration at C11L, 1~7 October.

3.2.2. Analysis of Indoor Ammonia Concentration Level and Distribution

The ammonia gas concentration data with the NIAP on/off at different measuring spots on 8 October 2018 were compared in Figure 10. When the NIAP was turned off, the ammonia concentrations were generally within the range of 360~430 ppb. After turning on the NIAP, the ammonia concentration of each measuring spot decreased significantly and stabilized between 76 ppb to 86 ppb. The maximum concentration of ammonia was 85.9 ppb, which did not exceed the threshold value of 263 ppb. By using Equation (9), the ammonia purification efficiency at different measuring spots was calculated. The purification efficiency at different spots was around 80%, which was higher than the prescribed value of JG/T 294-2010 [55] of 70%. The highest value was 81.33%, which occurred at the spot near the NIAP.

The ammonia gas distributions with the NIAP on/off are demonstrated in Figure 11. It can be seen that along the Y-axis direction, the ammonia gas concentration decreased significantly after the NIAP was turned on. The closer the measuring spot was to the NIAP, the lower the ammonia gas concentration can be achieved. The ammonia concentration at different heights had little variation rates and basically remained in the range of 1~3%. The average variation rates of ammonia gas concentration at different heights with the NIAP on/off were 2.99% and 1.88%, respectively, and the highest variation rates were 5.26% and 4.18%, respectively. Thus, the concentration distribution of ammonia along the Z-axis direction was more uniform.

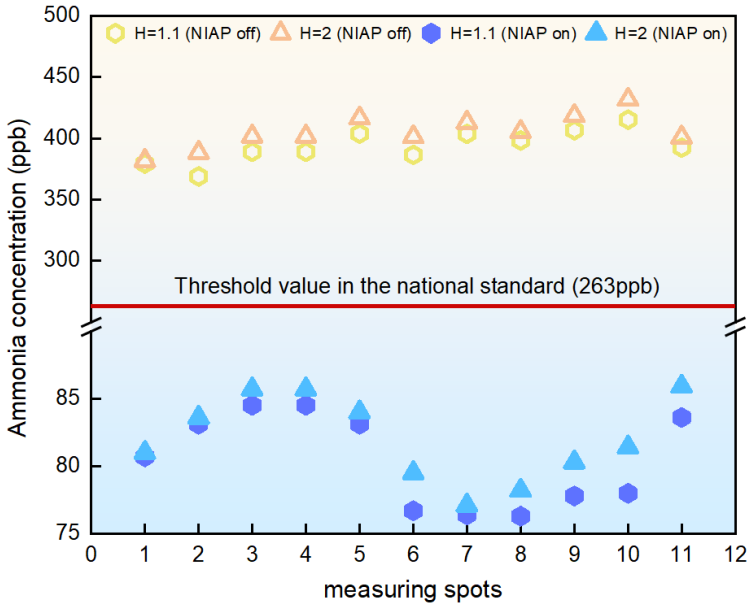


Figure 10. Ammonia gas concentrations with the NIAP on/off.

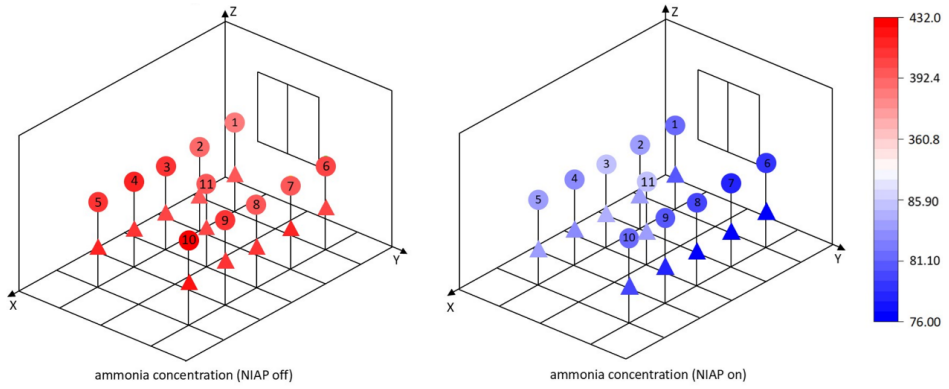


Figure 11. Spatial distribution of ammonia gas concentration in the bathroom.

When the NIAP was on, the ammonia concentrations at points 1~5 near the urinals first increased and then decreased along the X-axis direction, reaching the maximum value at point 3, which was 84.5 ppb. This was mainly because point 3 was in the middle of the two urinals, where the ammonia concentration was relatively high. In the meantime, the ammonia concentrations at points 6~10 near the NIAP first decreased and then increased along the X-axis direction, reaching the minimum value at point 8, which was 76.3 ppb. This was due to that point 8 was the closest to the NIAP, where the ammonia concentration was lower than that at the other measuring spots.

3.2.3. Analysis of Indoor Ozone Concentration

The concentration level of the produced ozone was analyzed in order to fully understand the performance of the NIAP. Figure 12 presents the ozone concentration at two heights (H = 1.1 m, H = 2 m) with the NIAP on/off. When the NIAP was turned off, the ozone concentration in the bathroom was in the range of 8~16 ppb. After the NIAP was turned on, the ozone concentration at each measuring spot increased, and the maximum ozone concentration was 72.8 ppb during the test. According to the Chinese national standard GB 3095-2012 [56], there are two levels of threshold values of indoor ozone concentration: level 1 (81.5 ppb) and level 2 (102 ppb). The maximum value of the measured ozone concentration (72.8 ppb) did not exceed either of the threshold values in the national standard [57].

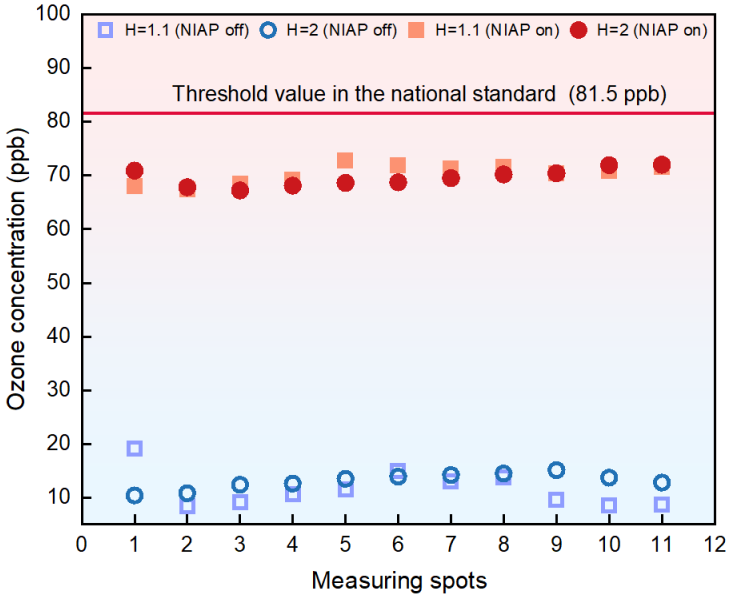


Figure 12. Ozone concentration at different heights with the NIAP on/off.

3.2.4. Analysis of Negative Ion Concentration

The concentration level of the generated negative ions was also presented in Figure 13 at different heights with the NIAP on/off. When the NIAP was turned off, the negative ion concentration in the bathroom was in the range of 80~150 ions/cm^3. After turning on the NIAP, an increase in negative ion concentration at each measuring spot can be observed, and the concentration of negative ions reaches 34,000~160,000 ions/cm^3. This means that a large amount of negative ions was generated by the NIAP which played a crucial role in removing the ammonia gas. By comparing the negative ion concentration at different heights, it can be found that the negative ion concentration at measuring spots at a higher height was lower than that at a lower height. In addition, Figure 13 also reveals that the negative ion concentration reduced significantly with the increase in the distance to the NIAP. Compared with the decrease in negative ion concentration along the vertical direction, the decrease along the horizontal direction is more obvious, which corresponds to the spatial distribution of ammonia gas concentration.

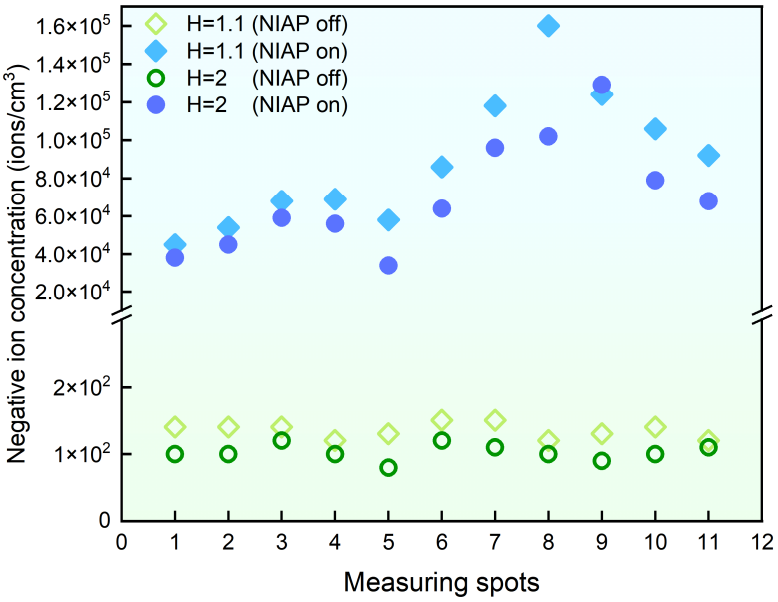


Figure 13. Negative ion concentration at different heights with the NIAP on/off.

4. Conclusions

In this paper, the influencing factors and purification performance of a negative ion air purifier for indoor ammonia gas removal were investigated. Two stages of experimental study were conducted including chamber tests and field measurements. Different influencing factors (upstream wind speed, operating voltage of the NIAP, initial ammonia gas concentration) on the ammonia gas removal performance of the NIAP were firstly investigated through a series of experiments. Then, indoor field measurements of ammonia gas, ozone, and negative ion concentrations in a real bathroom were performed for various cases with the NIAP turned on and off. The main conclusions are as follows:

The chamber experiments revealed that operating and environmental factors including upstream wind speed, degree of operating voltage, and initial ammonia gas concentration have great influences on the ammonia gas removal efficiency of the NIAP. The ammonia gas removal efficiency of the NIAP increased when the degree of operating voltage rose from 2.0 kV to 2.5 kV, and it dropped with the increase in the operating voltage when the operating voltage exceeded 3.0 kV. The ammonia gas removal efficiency was increased with lower upstream wind speed, and it first increased and then decreased as the initial ammonia gas concentration rose. Among these factors, the change in applied voltage has a significant effect on the ammonia removal efficiency; with the increase in applied voltage, the ammonia removal efficiency can be increased by 13.7%, and the ammonia removal efficiency can reach 95.8% when the degree of operating voltage was at gear 3 (3.0 kV).

The field measurements in a real bathroom indicated that, when the NIAP was turned on, there was an obvious decrease in ammonia gas concentration in the bathroom from its initial value of 360~430 ppb to 76~86 ppb, which was below the national standard of 263 ppb. In general, the ammonia gas removal efficiency of the NIAP was about 80%.

In terms of spatial distribution of ammonia gas and other by-products when the NIAP was on, the concentration distribution of ammonia on the horizontal plane decreased significantly along the Y-axis direction, and the distribution of ammonia concentration along the Z-axis direction was more uniform and its variation rates remained in the range of 1~3%. The maximum ozone concentration was 72.8 ppb, which was below the threshold value of the Chinese national standards. The negative ion concentration increased at each measurement point when the NIAP was on, and it decreased significantly when the distance of the measurement points from the NIAP increased.

This study showed that the negative ion air purifier had great potential in effectively removing ammonia from the bathroom, with a removal efficiency of up to 80%, and the maximum ammonia concentration in the bathroom did not exceed the relevant national standards. Although this study reveals that negative ion air purifiers are effective in removing bathroom ammonia, there are still some limitations that can be further investigated. Future studies can be focused on the long-term effects of the NIAP under different temperature and humidity conditions, as well as their effect on ammonia removal efficiency. The optimal installation position of the purifier and its purification effect was not discussed in this study. Future research can be conducted on the influence of by-products on ammonia removal through chemical composition analysis. Potential applications of the NIAP in various indoor environments and its long-term impact on air quality, as well as the generalizability of their findings to other environments, can also be discussed. The overall performance of the negative ion purifier in removing different types of pollutants including PMs and ammonia can also be compared in the future.

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and R.Z.; visualization, Z.L.; supervision, J.C.; project administration, J.C.; funding acquisition, Y.L. (Yilin Li). All authors have read and agreed to the published version of the manuscript.

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Nomenclature

M:	gas molecules entering the gap
A:	reactant molecule or atom
*:	representative excited state
e:	electronics
e*:	higher energy electron
O	oxygen atom
H	hydrogen atom
O_2	oxygen
O_3	ozone
NH_2	amino
NH_3	ammonia
NH_x	nitrogen deposition
OH	hydroxyl radical
H_2O	water
η	removal efficiency (%)
N_1	upstream ammonia gas concentration (mg/m^3)
N_2	downstream ammonia gas concentration (mg/m^3)
Y	coefficient of determination
X_1	operating voltage (KV)
X_2	upstream wind speed (m/s)
X_3	initial ammonia concentration (mg/m^3)

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