Experimental study of removing benzene from indoor air by needle-matrix to plate streamer discharge

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Abstract. The degradation of benzene by needle-matrix to plate streamer discharge was investigated at normal temperature and pressure in indoor air. The effects of benzene initial concentration, air speed, discharge power and relative humidity (RH) on benzene removal rate were systematically studied. Meanwhile, the benzene removal efficiencies by adding MnO2/ SiO2-active carbon catalyst to the system were also studied. The results showed that the benzene removal rate increased with the rise of the air speed and discharge power, decreased with the rise of the benzene initial concentration, and firstly increased and then decreased with the rise of the of RH. Under the same experimental conditions, adding MnO2 catalyst to the system did not significantly improve the removal efficiency of benzene.

1. Introduction
With the continuous improvement of living standards, more and more people are realizing the importance of indoor air quality. As one of the common volatile organic compounds (VOCs) pollutants in indoor, benzene has caused wide concern on its damage for human health [1,2]. Non-thermal Plasma has attracted a lot of attentions in the field of VOCs treatment by its high efficiency, simple process and low energy consumption [3-5]. Until now, many researchers have focused on dielectric barrier discharge (DBD) and pulsed corona discharge, but they are not too concerned about direct current (DC) corona discharge. In this study, the degradation of benzene by needle-matrix to plate DC streamer discharge was investigated in a closed chamber of 0.4 m³, and the effects of discharge parameter, air parameter and catalyst on benzene removal efficiency had also been discussed.

2. Experimental Setup
The experimental system is shown in figure 1. The needle-to-plate distance is 25 mm, and the needle-to-needle distance is 20 mm. There are 97 needles in the matrix with needle radius 1 mm and length 5 mm. Discharge power is supplied by ZGF-DC high-voltage generator and the applied voltage is measured by a Tek P6015A divider connected with an HP 54503 digital oscilloscope. The flow rate in electrical field is measured by ZRQF anemometer. The manganese oxides catalyst is 10 mm thickness per layer with hexagon holes of 2 mm side length. Benzene solution is placed into a water bath and benzene vapor is fed into closed chamber by air pump. The concentration of benzene in closed chamber is controlled by air flow rate as well as water temperature, and then is measured by

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PID 312 gas chromatograph.

Figure 1. Experimental setup.

3. Results and Discussion

3.1. Benzene natural attenuation

The concentrations of Benzene in closed chamber were kept at 0.35, 0.70 and 1.05 mg m\(^{-3}\). The flow rate in the electric field was kept at 2.8 m s\(^{-1}\), and the discharge power and relative humidity (RH) were 9 W and 20 %, respectively. The variation trend of benzene degradation rate was studied under three concentrations.

As shown in figure 2, each of three benzene concentrations has a slight fluctuation during discharge 90 min. Benzene concentration slowly decreased with discharge time (t), but was not exceeding 9 %. Considering that some benzene could collide with aerosol and then adsorbs at the chamber surface in the discharge process, the theoretical benzene value should be lower than the obtained results. Hence, the natural reduction does not significantly affect benzene removal efficiency by discharge, and its value at the same time will be deducted in the following experiments.

3.2. The effect of air speed on benzene removal rate

The concentration of benzene in the closed chamber was kept at 0.70 mg m\(^{-3}\). The flow rate of air in
the electric field was adjusted by auto-transformers and its values were set as: 0.5 m s\(^{-1}\), 1.0 m s\(^{-1}\), 2.0 m s\(^{-1}\), 2.4 m s\(^{-1}\) and 2.8 m s\(^{-1}\), respectively. The variation trend of benzene degradation rate under different flow rates were studied with discharge power 9 W and RH 20 %.

![Figure 3](image)

**Figure 3.** Relationship between benzene removal efficiency and discharge time. (\(\Diamond 0.5 \text{ m s}^{-1}\); \(\nabla 1.0 \text{ m s}^{-1}\); \(\triangle 2.0 \text{ m s}^{-1}\); \(\odot 2.4 \text{ m s}^{-1}\); \(\Box 2.8 \text{ m s}^{-1}\))

As shown in figure 3, the benzene removal efficiency increased with improved flow rate, but this trend was not obvious when its value exceeded 2.4 m s\(^{-1}\). The reason is probably that the benzene removal efficiency by discharge under unit time reached dynamic balance with increased air speed, because the energy input in the closed chamber was fixed. The removal efficiency under five flow rates were 55.7 %, 62.9 %, 78.6 %, 81.4 % and 82.9 %, respectively. It was thus clear that the benzene removal efficiency did not significantly change when air speed reached a certain value. Therefore, the air speed should be selected at 2.4 m s\(^{-1}\) if needle matrix to plate corona discharge reactor is applied in indoor air purification.

### 3.3. The effect of initial concentration on benzene removal efficiency

Within discharge 90 min, the variation trends of benzene removal rate under initial concentration 0.35, 0.70 and 1.05 mg m\(^{-3}\) were shown in figure 4. The relationship between discharge time and removal rate was discussed by trend line equations of 0-30 (stage1) min and 30-90 (stage2) min obtained from experimental data. The relevant experimental parameters were set as: power 9 W, air speed 2.4 m s\(^{-1}\) and RH 20 %.

As shown in figure 4, the benzene removal efficiency under three initial concentrations increased with discharge time. The removal speed rate of stage 1 was faster than that of stage 2, and the corresponding first order coefficient on a low to high initial concentration were 1.49, 1.32 and 1.26 respectively. The benzene removal speed almost kept unchanged in stage 2, the corresponding coefficients were 0.68, 0.66 and 0.69, respectively. In addition, the benzene removal efficiency decreased with the rise of the initial concentration and it reached maximum value at 0.35 mg m\(^{-3}\). The removal efficiencies on a low to high initial concentration were 88.6 %, 82.9 % and 81.9 %, respectively. This is because that the collision probability between each benzene molecular and high-energy electrons improved with the reduction of benzene concentration.

### 3.4. The effect of discharge power on benzene removal efficiency

The variation trend of benzene removal efficiency under different discharge power was shown in figure 5. The powers were kept at 9, 6.5, 4.5 and 2 W, respectively, and the other experimental parameters were same to section 3.3. As shown in figure 5, the benzene removal efficiency increased with the rise of the discharge power under different powers, but the magnification range gradually decreased. At 90 min, the efficiencies from 9 W to 2 W were 82.9 %, 77.1 %, 67.1 % and 44.3 %,
respectively. Moreover, the fluctuation of removal efficiency did not significantly change with the rise of discharge power.

![Figure 4. Relationship between benzene removal efficiency and discharge time. (□ 0.35 mg m⁻³; ○ 0.70 mg m⁻³; △ 1.05 mg m⁻³)](image)

![Figure 5. Relationship between benzene removal efficiency and discharge time. (□ P=9 W; ○ P=6.5 W; △ P=4.5 W; ▽ P=2 W)](image)

The discharge process can be divided into three parts: initial streamer discharge, glow discharge and spark discharge [6]. The characteristics of initial streamer discharge are low current and discharge instability, which leads to the fluctuation of removal efficiency in this stage. Then, more and more high energy electrons, active species and free radicals are produced with the rise of discharge power, leading to the improvement of benzene removal efficiency.

3.5. The effect of RH on benzene removal efficiency
In this part, the parameter RH was changed from 20 % to 60 % in order to investigate its effect to benzene removal efficiency. Other experimental parameters were the same with those in section 3.3. As known from figure 6, along with the rise of RH, the removal efficiency firstly increased and then decreased. The efficiencies of three RH were 82.9 %, 85.7 % and 80 %, respectively. The best RH value under our experimental condition should be 40 %.
This observation can be explained as follows: It is known that OH and O could effectively dispose benzene molecular. The amount of OH and O radicals increases with increased collision frequency between energetic electrons and water molecules [7, 8]. When the relative humidity is low, the collision frequency will be also less; on the contrary, the collision frequency will be high. On the other hand, with the rise of RH, more electrons will be absorbed by the increased H₂O molecular due to its electronegativity. This will lead to the reduction of density of energetic electrons, and the reduction of the collision frequency between energetic electrons and water molecules. At the same time, streamer discharge will be instable and the discharge current will sharply decrease when RH is relatively high. These will make the reduction of benzene removal efficiency.

In addition, the synergistic effect of plasma and MnO₂ catalyst on benzene degradation has also been investigated in this study. The comparison of the removal effects by plasma and plasma-MnO₂ had been obtained. However, comparing with plasma, the addition of MnO₂ catalyst did not significantly improve the benzene removal efficiency.

4. Conclusions

(1) There is a linear relationship between the benzene removal efficiency and discharge time, and the removal efficiency decreased with the rise of initial benzene concentration. Benzene removal rate slightly increased with the deduction of initial concentration in discharge stage 0-30 min, but did not significantly change in discharge stage 30-90 min.

(2) The benzene removal efficiency gradually increased with the rise of air speed. This trend was not obvious when air speed reached a certain value. The air speed should be selected as 2.4 m s⁻¹ under this experimental condition.

(3) The benzene removal efficiency gradually increased with the rise of discharge power, but magnification range gradually decreased. The fluctuation of removal efficiency weakened with the rise of power.

(4) Along with the rise of RH, the benzene removal efficiency firstly increased and then decreased. The best benzene removal efficiency appeared when RH is 40 %.

(5) Comparing with only plasma, the MnO₂-Plasma system probably could not significantly improve benzene removal efficiency.

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