The performance testing of new combinational air treatment system for underground projects

Hongyu Zhang¹, Chunlong Zhuang², Guangqin Huang³, Jie Yu, Yajiao Liu and Xiaodong Shen
¹, ², ³ Army Logistic University of PLA, Chongqing, China, 401311
Email: zhanghongyu1010@163.com

Abstract. Owing to the special request of environment and closeness, for example the underground structure, communication engineering and the forth, there are a lot of air pollutions (sulphur dioxide, nitrogen oxide and carbon monoxide, etc.) in the close and half close space. The air pollutions harm the health of the internal persons seriously. This topic studies all kinds of air purification modes, design the combined purification craftwork (photocatalytic oxidation, plasma and adsorption techniques) for underground engineering air pollution, develops a suite of combinational air purifying device, and finally conducts the performance test. The conclusions are obtained as follows: (1) the combinational air purification device has excellent treatment effect on the formaldehyde and CO gas. When the gas mixture goes through the photocatalytic oxidation module and the plasma module simultaneously, and then the adsorption module finally, the degradation rate of formaldehyde is up to 91.8%; in addition to separate activated carbon treatment, other treatment modes of the device are capable of purifying the CO gas, the purifying rate is between 77%~87%.(2) The combination air purifying device provide the hardware support for evaluation of the effectiveness of high efficient purification materials and combination of air purification process during engineering application.

1. Introduction
Human have experienced the harm of “Soot Pollution” and “Photochemical Smog Pollution”, now the third generation of pollution which is mainly about “Air Pollution” is coming, and especially indoor pollution is 5 to 10 times the outdoor pollution [1]. In the joint detection of China’s environment department, a total of more than 500 kinds of indoor harmful volatile organic compounds are found, peculiarly some of the harmful gas concentration is dozens of times or even one hundred times higher than outdoor. And it contains more than 20 kinds of strong carcinogenic substances such as formaldehyde and benzene [2]. Especially for close-space such as underground structure, communication engineering and the forth, due to its particularity, the factors influencing the internal air quality are mainly from diesel generators, personnel, decoration materials and other equipments. The indoor harmful air contains about 150–200 different compounds in the close-space, and some of the most harmful to human are CO, hydrocarbons, nitrogen oxides, lead compounds, particulate matter, formaldehyde, etc. Once these chemicals are absorbed by human body, it will produce very serious effect to human body. In the case of poor ventilation, pollutants will gather more and more, they affect each other, making concentration gradually increase. It will not only affect the user's health and emotion, but also cause fatigue, dizziness, memory loss, eventually lead to lower efficiency [3-6].

In order to guarantee the air quality of the close-space, the treatment of air pollutants in close-space must be studied, so that measures can be taken to optimize the environment quality of the close-space air. At present the treatment of air pollutant in close-space mainly include: photocatalytic technology,
plasma technology, adsorption technology and filtering technology [7]. But few researches are about the cooperation between various processing technologies. Moreover study of close-space air handling unit is mostly just for one or several pollution gases. It has a narrow range of application. Such as the invention devised by Li Jun and Chen Xu-dong, however, it can’t deal with various components, and also can’t adopt the method of combination for multi-level processing according to the different components of gas inside the close-space.

Based on the above analysis, this topic constructs a new combinational air treatment system for close-space, and carries out the research on the combinational effect of the photocatalytic technology, plasma technology and absorption on the platform of this system. On the basis of the experimental system, by integrating different pollution gas processing technology, this topic is aiming at seeking the best method of air pollutants degradation in close-space, effectively reducing the harm of internal personnel’s health and improving their work efficiency. At the same time, the establishment of the experimental system provides the hardware support for evaluation of the effectiveness of high efficient purification materials and combination of air purification process during engineering application.

2. Method or Experimental

In order to carry out the research on the combination of air purification process and provide hardware support for evaluation of the effectiveness of high efficient purification materials, this topic constructs a new combinational air treatment system for close-space. And it studies the combinational effect of the photocatalytic, plasma and absorption technologies on the platform of this system. Finally it seeks the effective treatment scheme of formaldehyde and CO gas.

2.1. Theoretical Background

This topic analyzes the reaction’s theoretical background of photocatalytic technology, plasma technology and absorption technology. so it can find the interior mechanism clearly, and search the most efficient treatment for air purification process.

(1) Photocatalytic technology. TiO\textsubscript{2} is a kind of N-type semiconductor material. The energy band gap is 3.2eV, which is equivalent to the light of 380 nm wavelength. When it is exposed to the ultraviolet radiation, it will produce photon generated electron $e_{CB}^-$ and electron hole $h_{VB}^+$. The electron and electron hole can migrate to the solid surface; respectively react with the dissolved oxygen and water. And they will produce highly reactive free radicals $\cdot OH$ and $\cdot O_2$ which are highly active catalysts for the deep oxidation of formaldehyde [8]. The main process of formaldehyde’s decomposition is shown in figure 1 below.

![Figure 1. Dominant pathways leading to the destruction of CH\textsubscript{2}O molecules by photocatalytic technology](image)

(2) Plasma technology. The technology can be divided into two parts: electrons directly react with formaldehyde; the reactive groups produced by the electric field react with formaldehyde [9-10]. The energy got by the electron in the process of discharge ranges from 2eV to 20eV. The main process of formaldehyde’s decomposition is shown in figure 2 below [11-12].
Figure 2. Dominant pathways leading to the destruction of CH₂O molecules by plasma technology.

Figure 3. The interactions of photocatalytic technology and plasma technology.

(3) Absorption technology. Activated carbon is a porous carbon material; its highly developed porous structure makes it have large surface area. So this kind of highly developed pore structure - capillary constitutes a strong adsorption force field. It can absorb poisonous and harmful gases (impurities).

(4) The combination of photocatalytic and plasma technology. Their cooperation can enhance the removal of pollutants completely. The plasma can produce ultraviolet and the ultraviolet will arouse the reaction of TiO₂; The plasma can produce a number of high activity of neutral particles and they will promote the activation of photocatalyst; The O₃ gas produced by the plasma can promote the efficiency of photocatalyst; TiO₂ is something like the dielectric material and it will enhance the electric field of plasma; TiO₂ is something like the adsorbent and it will enlarge the time the gas stays on the catalyst [13]. The sketch map is shown in figure 3.

2.2. Air Treatment System

This air treatment system is mainly composed of adsorption module, photocatalytic module, the low temperature plasma module, fresh air purification module and reserved air processing module, electric air valve and automatic control module, etc. The principle of system is shown in figure 4. Air handling unit can carry out air treatment plan independently, and also can combine a variety of treatment scheme without interference between each other by the upper machine control system. What’s more, according to the requirements of special air pollutant treatment, it can add new processing module for function expansion by the reserved air processing module interface. This system uses many kinds of processing methods to purify complex pollution gases in close-space, and improve the efficiency of the air pollution treatment. It’s both agile and convenient.


2.3. Air Treatment Scheme

The design requirement of close-space air treatment system is to conduct air treatment independently, and also combine a variety of air treatment modules without interference each other according to the demand of pollutant treatment.

2.3.1. Independent Scheme. In view of the harmful ingredient of close-space pollution gases, air treatment system can take the following independent air treatment scheme:

1. Photocatalytic technology. This technology mainly uses the photocatalysis of the catalyst; oxidize the harmful substances adsorbed on the surface of the catalyst to harmless substances [14-15]. Air treatment system uses the TiO$_2$ light catalyst made by the laboratory as air purification material.

2. Plasma technology. The plasma is rich in electrons, ions, free radicals and the excited state, they open the molecular bond and at the same time produce free radicals and O$_3$, thus deal with the low concentration VOCs (volatile organic compounds) in the air [16-18].

3. Absorption technology. This technology takes use of certain substances with absorption ability to adsorb the harmful pollutant for the goal of purifying the air, such as activated carbon fiber, Al$_2$O$_3$, silica gel, molecular sieve, etc [19-20]. With comprehensive comparison, the air treatment system uses new type activated carbon as the adsorbent.

2.3.2. Combinational Scheme. By controlling the electric air valve, this system can carry out combinational air technology (two kinds of treatment technologies or combination of three processing technologies) based on air pollutant treatment requirements. And it will optimize the air environmental quality in close-space. According to different target pollutants, each processing unit can be combined arbitrarily and changed in order to achieve the best effect. The concrete combinational schemes are as follows:

1. The combination of plasma technology, adsorption technology, air heat and wet treatment technology. The scheme is mainly used for VOCs processing. The addition of adsorption technology can make up for the lack of a single plasma technology by reducing the by-products' pollution caused by plasma technology [21].

2. The combination of photocatalytic technology, adsorption technology, air heat and wet treatment technology. This scheme can combine photocatalytic technology and adsorption technology efficiently: activated carbon has strong adsorption ability for low concentration organic gases, and combine the ability of TiO$_2$’s purification for organic gases; the low concentration pollutant can be significantly improved. At the same time, activated carbon can also adsorb the by-products caused by catalytic oxidation of TiO$_2$ [22].

3. The combination of photocatalytic technology, plasma technology, air heat and wet treatment technology. Photocatalytic technology and plasma technology both produce a lot of intermediate...
processing pollutants. Their cooperation can enhance the removal of pollutants completely [23].

(4) The combination of photocatalytic technology, plasma technology, adsorption technology, air heat and wet treatment technology. This scheme can effectively combine three kinds of processing technologies’ advantages. It can not only effectively enhance the removal of pollutants completely; also can avoid the secondary pollution of reaction by-products [21-23].

2.4. Experimental Process

Among various pollution gases, formaldehyde pollution with its wide sources, heavy pollution and hard purification become a top priority. Formaldehyde ranks second in the list of toxic chemicals in China. And it’s identified by the World Health Organization as the suspected carcinogen [24]. In addition, various types of fuel power generation equipment in the underground close-space will produce large amounts of toxic or harmful gases, such as CO which is the main pollutant. Therefore, in order to explore the different effect of the combinational scheme for the air treatment system, the experiment chooses formaldehyde and CO gas as the goal pollutant. And it researches the change of degradation rate respectively. In addition, the formula of the degradation rate is written as:

\[ \eta = \frac{C_0 - C_t}{C_0} \times 100\% \quad (1) \]

where \( \eta \) represents the degradation rate, \( C_0 \) the initial concentration, \( C_t \) the final concentration.

2.4.1. Purification Experiment of Formaldehyde. The purification experiment of formaldehyde includes three independent ones and three combinational ones. The formaldehyde gas is produced by 40% formalin solution and the initial concentration is about 2.0 mg/m³. As for the air conditioning system, the supply air temperature is 25°C, relative humidity is 75%, wind speed is 1.34 m/s. Different treatment schemes are carried out by controlling the air valve, and the change of formaldehyde concentration is recorded while the system is running for 60 min.

2.4.2. Purification Experiment of CO. The purification experiment of CO includes three independent ones and four combinational ones. The CO gas is produced by burning cigarette and the initial concentration is about 14 PPM. As for the air conditioning system, the supply air temperature, relative humidity and wind speed is the same as purification experiment of formaldehyde. Different treatment schemes are carried out by controlling the air valve, and the change of CO concentration is recorded while the system is running for 60 min.

3. Results and Discussion

3.1. Purification Experiment of Formaldehyde

3.1.1. Independent Scheme. The result is shown in figure 7 below. With plasma circulation processing for 60 min, the degradation rate of formaldehyde reaches 55.1%, but the degradation rate gradually slows down. At the same time, a large number of O₃ is detected at the end of the reaction. With photocatalytic treatment for 60 min, the degradation rate of formaldehyde reaches 40.6%, the degradation rate appears first quick and back slow trend overall. With adsorption treatment for 60 min, the degradation rate of formaldehyde reaches 38.1%, in the first 20 min, due to the strong adsorption of the adsorbent, the degradation rate of formaldehyde is fast. However, as the reaction progress, the degradation rate gradually slows down because of the adsorbent tending to saturation.

Based on the above experiment, on the design of the combined air treatment, the adsorption treatment is set behind photocatalytic treatment and plasma treatment because of the existence of the strong oxidizing O₃ after the plasma treatment. This process can adsorb O₃ and CO₂ effectively.
3.1.2. Combinational Scheme. This experiment mainly tests the synergy effect between photocatalytic technology and plasma technology. The design of experiment is as follows:

A. Formaldehyde gas goes through the photocatalytic module and the plasma module simultaneously, and then the adsorption module.

B. Formaldehyde gas goes through the plasma module, then the photocatalytic module, and then the adsorption module.

C. Formaldehyde gas goes through the photocatalytic module, then the plasma module, and then the adsorption module.

The result is shown in figure 8 above. It shows that changes of formaldehyde degradation rate show great difference under different technological processes. The change of A is the largest, B is the second and C is the smallest. The main reason is:

1. A number of high activities of neutral particles produced by plasma can float to the photocatalytic layer along with the flow, and then it can promote the activation of photocatalyst [25].

2. Part of the O$_3$ produced by plasma can reach the photocatalytic layer and promote the activation of photocatalyst. At the same time, photocatalysis can speed up the adsorption and decomposition of O$_3$ [26].

3. The strong electric field of plasma reacts with the electron inspired by the photocatalyst. During the coupling reaction, the photocatalyst TiO$_2$ has the effect of certain dielectric, which can strengthen...
the local electric field [27].

(4) Sufficient uv light can make the activated photocatalyst fully adsorb the neutral group particle produced by plasma and molecules of formaldehyde, thus promoting the oxidation and degradation of formaldehyde gas.

(5) Photocatalytic technology and plasma technology both produce a lot of intermediate processing pollutants. Their cooperation can enhance the removal of pollutants completely.

At the same time, there is no excess O₃ detected because of the adsorption of the adsorption module.

3.2. Purification Experiment of CO
The result is shown in table1 and figure9. Table 1 shows the purification effect of CO by listing the initial concentration, the final concentration and the degradation rate of CO. Figure 9 shows the relationship

| Scheme               | Photocatalyst | Plasma                  | Activated carbon | Photocatalyst + Plasma | Photocatalyst + Activated carbon | Plasma + Activated carbon | Photocatalyst + Plasma + Activated carbon |
|----------------------|---------------|-------------------------|------------------|------------------------|----------------------------------|---------------------------|------------------------------------------------|
| Initial concentration (PP M) |               |                         |                  |                        |                                  |                           |                                                 |
|                      | 14            | 13                      | 13               | 15                     | 15                               | 14                        | 15                                             |
| Final concentration (PP M) |               |                         |                  |                        |                                  |                           |                                                 |
|                      | 2             | 3                       | 6                | 2                      | 2                                | 2                         | 2                                              |
| Degradation rate(%)   | 85.7          | 76.9                    | 53.8             | 86.7                   | 86.7                             | 85.7                      | 86.7                                           |
Figure 9. The relationship between concentration of CO and Purification time

Between concentration of CO and Purification time for 60 min. It is found that the concentration of CO becomes stable after 30 min for each scheme in figure 9. Taking the independent photocatalytic technology for example, it’s found that the degradation rate reaches 85.7% after 30 min, so it is for the independent plasma technology and the combinational schemes. On the whole, in addition to the separate activated carbon adsorption treatment, other treatment modes of the device are capable of purifying the CO gas; the degradation rate is between 77%~ 87%.

4. Conclusion

This topic designs the combined purification craftwork (photocatalytic oxidation, plasma and adsorption techniques) for Close-Space air pollution, develops a suite of combinational air purifying device, and finally conducts the performance test. The results show that:

(1) With the research on the combinational effect of the photocatalytic technology, plasma technology and absorption, different pollution gas processing technologies can be integrated effectively in order to seek the best method of air pollutants degradation.

(2) The combinational air purification device can develop air treatment technology independently (by using the low temperature plasma technology, photocatalytic oxidation technology and adsorption technology). And it also can carry out combinational air technology based on air pollutant treatment requirements (two kinds of treatment technologies or combination of three processing technologies).

(3) The combinational air purification device has excellent treatment effect on the formaldehyde and CO gas.

References

[1] Zhang Li-zhu, Yu Lei, Tang Mou-sheng. The harm of indoor air pollution and countermeasures [J]. Environmental Science Society Academic Essays of China, 2009:854-857.

[2] Tan You-jin, Qian Run-sheng, Tang Xin-ming. Chemical disaster and rescue [M]. Beijing: Chinese People’s Liberation Army Publishing House, 2004:84-95.

[3] Gao Jun, Song Tian-heng, Fang Yan-bing, Chen Ming. Application of inductive air jet to underground garage for reducing both surface condensation and CO pollution in hot and humid climate [J]. Journal of Tongji University.2013, 41:875-881.

[4] Gao Jun-min, Chen Lei, Zhang Ying, Jin Fen, Li Bai-zhan. Occurrence and pollution source of TVOC in underground stores in Chongqing [J]. Journal of Central South University. 2012, 43:4554-4558.

[5] Mohammed Nurul Lzma, Othman Nurfadhilah, Baharuddin Khairul Bariyiah. Air quality profile in an enclosed car park [J]. Applied Mechanics and Materials.2014, 567:3-7.
[6] Cheng Yu-Hsiang, Yan Jhih-Wei. Comparisons of particulate matter, CO, and CO2 levels in underground and ground-level stations in the Taipei mass rapid transit system [J]. Atmospheric Environment. 2011, 45: 4882-4891.

[7] Rasalingam Shivatharsiny, Peng Rui, Koodali Ranjit T. An insight into the adsorption and photocatalytic degradation of rhodamine B in periodic mesoporous materials [J]. Applied Catalysis B: Environmental. 2015, 174-175: 49-59.

[8] Lu Yuan-wei, Ma Chong-fang, Xia Guo-dong. Researches on the photocatalytic decomposition of indoor formaldehyde for air purification [J]. Acta Energiae Solaris Sinica. 2004, 25: 542-546.

[9] Li Jian, Ma Guang-da. The mechanismic analysis and experiment on controlling volatile organic compounds (VOCs) with corona discharge [J]. Journal of Xi’an University of Architecture & Technology. 2000, 32: 24-27.

[10] Zhang Ren-xi, Hou Jian. Application of plasma technology to the environmental protection (I) [J]. Shanghai Chemical Industry. 2000, 25: 4-5.

[11] Moo Been Chang, Chin Ching Lee. Destruction of formaldehyde with dielectric barrier discharge plasma [J]. Environ Sci Techno. 1995, 29: 181-186.

[12] Daniel G Storch, Mark J Kushner. Destruction mechanisms for formaldehyde in atmospheric pressure low temperature plasmas [J]. J Appl Phys. 1993, 73: 51-55.

[13] Folli Andrea, Strm Michael, Madsen Thomas Pilegaard. Field study of air purifying paving elements containing TiO2 [J]. Atmospheric Environment. 2015, 107: 44-51.

[14] Aghighi Alireza, Haghighat Fariborz. Using physical-chemical properties of reactants to estimate the performance of photocatalytic oxidation air cleaners [J]. Building and Environment. 2015, 85: 114-122.

[15] Andryushina Natalya S., Stroyuk Oleksandr L... Influence of colloidal graphene oxide on photocatalytic activity of nanocrystalline TiO2 in gas-phase ethanol and benzene oxidation [J]. Applied Catalysis B: Environmental. 2014, 148-149: 543-549.

[16] Thevenet F., Sivachandiran L., Guaitella O... Plasma-catalyst coupling for volatile organic compound removal and indoor air treatment: A review [J]. Journal of Physics D: Applied Physics. 2014, 47.

[17] Xiao Gang, Xu Wei-ping, Wu Rong-bing. Non-thermal plasmas for VOCs abatement [J]. Plasma Chemistry and Plasma Processing. 2014, 34: 1033-1065.

[18] Jia Bao-jun, Chen Yang, Feng Qin-zhong. Research progress of plasma technology in treating NO, SO2 and Hg0 from flue gas [J]. Applied Mechanics and Materials. 2013, 295-298: 1293-1298.

[19] Krou N.J., Battenau-Gener I., Belin T... Reactivity of volatile organic compounds with hydrated cement paste containing activated carbon [J]. Building and Environment. 2015, 87: 102-107.

[20] Markowicz Pawel, Larsson Lennart. Improving the indoor air quality by using a surface emissions trap [J]. Atmospheric Environment. 2015, 106: 376-381.

[21] Xie Zhi-hui, Ye Qi-zheng, Chen Lin-gen, Li Jin. Progress in removal of VOCs by combinations of discharge plasma and other physical-chemical methods [J]. High Voltage Apparatus. 2004, 40: 449-452.

[22] Gao Li-xin, Lu Ya-jun. Present status and improvement of indoor air purifier [J]. Journal of Harbin Institute of Technology. 2004, 36: 199-201.

[23] Wang Bin, Zhang Huan, Lu Shi-chang. The study on photo catalysis and discharge plasma treating VOCs and bacterium [J]. Journal of Hebei Institute of Architectural Science and Technology. 2004, 21: 17-20.

[24] Liang Wei-hui, Yang Xu-dong. Indoor formaldehyde concentration increase and decay pattern in a real residential unit [J]. Lecture Notes in Electrical Engineering. 2014, 261: 347-353.

[25] Zhou Fei, Yang Xue-chang, Gao De-li. Experimental study of air cleaning using a plasma with TiO2 catalyst [J]. J Tsinghua Univ(Sci & Tech). 2007, 47(4): 10-13.

[26] Zhang Shao-jun, Wang You-jun, Hou Li-an. The current research status of air pollution control by plasma-photocatalyst hybrid system [J]. Environmental Science and Technology. 2007, 30(8): 107-111.

[27] Lilie, Zhou Zhi-gang, Wang Hui-juan. Pulsed Discharge Streamer Lamp-house Available for Photocatalysis Research [J]. Chemistry. 2005, (1): 57-61.