Roles of UV light strength and auxiliary electric field in the photocatalytic degradation effect of organic contaminant

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Abstract: The accumulation of contaminants on the electrical devices could adversely affect the operation. The present work used photocatalytic functional material to coat on the surface of the electrical devices to prevent the influence of organic contamination. This kind of material was mainly composed of TiO2 that can remove the contamination by the effect of photooxidation. The photocatalysis was affected by the strength of UV light and electric field. In the experiment, methyl orange (MO) was used as the organic contaminant. The effect of UV light and auxiliary electric field were analysed based on the theoretical simulation. With the stronger UV light, more electron–hole pairs were generated, photocatalytic effect became more pronounced. With the auxiliary electric field, the recombination of electron and hole could be restrained that would increase the productive rate of hole; therefore, more hydroxyl radical will be produced to degrade MO.

1 Introduction
Social economy is developing rapidly, tailpipe emission augments with the increase of industrial emission and domestic emission and the environment is worsening in some areas. People have to face problem caused by the worse environment. There are different kinds of particles exist in the air such as dust, smoke, fog, haze and so on [1]. The contaminated environment not only affects the normal life of people but also has influence on the electrical devices. Therefore, the safe operation of power grid is under serious threat and the amount of system faults caused by the particles due to contamination gradually increases.

Some electrical devices have to operate in the more complex environments. In these environments, undesired particles could possibly adhere to the surface of electrical devices exposed to air in the presence of contamination [2, 3]. It is inevitable that the electrical devices perform in exposed air. The contamination will generate different effect to the different electrical devices. Outdoor conductors, shielding rings, insulators, bushing, are easily influenced by contaminant particles due to the high electric field near their surfaces, which could reach the order of kV/cm. The application of photocatalytic coating on the electrical devices is reported by Vinodgopal et al. in [24] that external electric field could prevent the recombination of electron and hole, then promote the separation of photon-generated carrier and improved the degradation rate of chlorophenol. Hidaka designed three different deposition methods to fabricate thin film electrodes and compared their photocatalysing efficiency. It was found that the type of electrode had influence on photocatalysis and the photoactivity was affected by the crystalline form, film thickness and film transparency [25]. Fan et al. [26] used composite Bi2WO6/CA electrode as photocatalyst, the increasing of the applied voltage and pH could promote electrosorption, the synergistic effect of electrosorption and photocatalysis was discovered. Dai et al. [27] used piezoelectric material to generate an alternating electric field to promote photocatalytic effect. Phan et al. [28] investigated the relationship of light intensity and photocatalytic degradation. Jinqui et al. [29] studied the influence of electric field to the photocatalysis; however, the highest electric field strength was only 16.67 V/cm in the experiment. The influence of electric field to the photocatalysis in higher electric field strength has been studied.

Many outdoor electric power equipment, such as metal conductors, shielding rings, insulators, bushing, are easily influenced by contaminant particles due to the high electric field near their surfaces, which could reach the order of kV/cm. The application of photocatalytic coating on the electrical devices is still scarce nowadays. In the present paper, the photocatalytic degradation of the typical organic pollutants in the surface of the TiO2 coating was carried out, the effects of ultraviolet light together with auxiliary electric field were studied by both experiment and theoretical computation.

2 Method of experiment

2.1 Fabrication of coating of the aluminum blocks

In this investigation, aluminium blocks with dimensions of 30 mm × 30 mm × 3 mm were used as substrates. In the first step of the fabrication, Al blocks were polished before they were cleaned and dried. Cleaning of the Al blocks was done using water-based cleaner before they were dried by a blower at room temperature.

The TiO2 blocking layer was prepared by mixing 1 unit by mass of C11H22O8Ti (Alfa, 75 wt% in isopropanol) and 4 units by mass
of C2H5OH (Acros) using a magnetic stirrer running for 30 min at a speed of 1000 rpm. TiO2 blocking layer was used as the first coat on Al blocks to decrease the recombination of electron–hole pairs [30–35] as preventing recombination can improve photocatalysis effect [36] (Table 1).

The mesoporous TiO2 layer was made by mixing 1 unit by mass of TiO2 paste (Dyesol, 30 NR-D, TiO2 19.0 wt%), 1 unit by mass of C10H18O (Acros, alpha-Terpineol) and 5 units by mass of C2H5OH using magnetic stirrer operating for 12 h at a speed of 1000 rpm. Mesoporous TiO2 layer plays the main role in photocatalysis and 30 nm size crystalline TiO2 was used in this paper.

After the preparation of the coating materials, Al blocks were coated, first, with the TiO2 blocking layer using a spin coater at a speed of 1500 rpm for 30 s (Fig. 1). In the next step of the process the block was placed on a hot plate at 125°C for 10 min. Then, the mesoporous TiO2 layer was coated on the Al blocks using the same spin coater for 30 s. Finally, the TiO2-coated Al blocks were annealed on a programmable hot table at 550°C for 1 h [37] (Fig. 1). Around 55 and 90 mg/L methyl orange (MO) solutions were used as typical organic contaminations because they had the ability of colour deterioration during the process of chemical degradation [38].

### Table 1 Mixing ratios of the chemicals to form the layers

| Chemicals                  | Mass per cent | TiO2 blocking layer | Mesoporous TiO2 layer |
|----------------------------|---------------|----------------------|-----------------------|
| C2H5OH                     | 80%           | 72%                  |                       |
| C16H28O6Ti                 | 20%           | —                    | —                     |
| TiO2 paste                 | —             | 14%                  | —                     |
| C10H18O                    | —             | —                    | 14%                   |

The experimental setup is shown in Fig. 2a. Parallel-plate electrodes were used in the experiments. The distance between plate electrodes is 20 cm and the diameter of plate electrode is 30 cm. The aluminium block is placed at the centre of lower plate electrode. DC high voltage is applied on the upper plate electrode through 1 MΩ protective resistor. There is an epoxy resin insulation board between the protective resistance and upper plate electrode. Four cylindrical pillars are also made of epoxy resin insulation material.

There are six fluorescent light bulbs producing UV light, surrounding the test setup. The strength of UV was changed by switching fluorescent light bulbs. UV lamps stick to wall of the box on different position and the strength of UV light is changed by switches of the fluorescent light bulbs. The spectrum of UV light was measured by UV spectrum analyser (model OHSP-350UV, wavelength range within 200–850 nm) shown in Fig. 3. The abscissa of peak is 369 nm that satisfies the conditions for photocatalysis [39]. The UV intensity, also defined as the averaged UV irradiation energy over a period of time (one hour in the present work) could be obtained by the UV-integrator (model UV-int 150) in the wavelength 250–410 nm. The UV intensity is used in the present paper to represent for light intensity.

The data in relation to UV intensity was recorded by a UV spectrum analyser for 1 month in the district of North China Electric Power University in June as shown in Fig. 4.
The illumination intensity was under 3000 mW/m² for most days of June. The illumination intensity was 2000 mW/m²² average in sunny days and below 1000 mW/m² in cloudy and rainy days. So the range of illumination intensity was designed to be in the range of 0–3 W/m² during the experiment.

Fig. 5 shows the calculation result of electric field with the Al block on the centre of the lower electrode. The finite element method was used in the calculation. The applied voltage on the upper plate electrode was 40 kV, the lower plate was specified as ground with the electric potential 0 kV, the distance between the plate electrodes was 20 cm. The epoxy props were neglected in the calculation. It is obvious that the electric field of Al block on the centre of the lower electrode is uniform although there exists certain edge effect in the upper and lower electrodes. The finite element calculation result for the surface of Al block is 2.26 kV/cm in this case. In this investigation, under different applied voltages and inter-electrode distances, no partial discharge occurred, hence, the potential impact of space charge on photocatalytic was avoided, the electric field strengths on the MO sample were 0, 1.06, 2.13, 3.19, 4.26, 5.32, 6.39, 7.45 and 8.52 kV/cm, respectively.

Around 0.3 g MO solution was added on the coated aluminium block to simulate organic contamination. The total mass of the block together with the MO solution was recorded every 30 min by a precise electronic scale. Each sample was exposed to UV light for 120 min.

2.3 Greyscale image processing

The color to grey scale method was used in this work to quantify the change during the degradation of MO. Every point of greyscale image was corresponding to a gray value. Different grey value presented different greyscale in grey image. The minimum value 0 was corresponding to black. The maximum value 255 was corresponding to white. Colour image was divided into points by pixel of the image. Every point defined as (x, y) of colour image was composed of three primary colours red \( R(x,y) \), green \( G(x,y) \) and blue \( B(x,y) \). \( R(x,y) \), \( G(x,y) \) and \( B(x,y) \) could be transformed to grey value \( \text{Grey}(x,y) \) by (1) as follows [40]:

\[
\text{Grey}(x,y) = R(x,y) \times 0.1 + G(x,y) \times 0.1 + B(x,y) \times 1.3 \quad (1)
\]

3 Results

3.1 Effect of UV strength

During the experiments, 0.3 g, 55 mg/L MO solution was placed on the aluminium blocks having dimensions of 30 mm by 30 mm. The ambient temperature and the relative humidity were in a range of 25–28°C and 56–58%, respectively. A digital camera was used to get the photographs of the samples under similar conditions. The samples were tested at UV strengths of 0, 0.5, 1, 1.5, 2, 2.5 and 3 W/m². Fig. 6 exhibits the photograph results of the samples under 0, 1, 2 and 3 W/m² UV strengths without applied electric field.

As can be seen from Fig. 6a, it is difficult to degrade MO without the presence of UV light. Thus, the photocatalysis process requires suitable amount of UV light. In the second and the third sets of samples, the influence of photocatalysis was quite obvious as can be seen in Figs. 6b and 6c. The colour of the third sample was lighter than the second sample for UV exposure time of 120 min indicating that the higher UV light intensity can promote further photocatalysis.

The greyscale image of the samples under 3 W/m² UV light strengths at 0, 60 and 120 min is presented in Fig. 7. With the degradation of MO, the greyscale image will be brighter and the grey value will increase. The averaged grey value of the 200 × 200 pixel of the greyscale image was calculated as the grey value of the sample.

The grey value of the samples under different UV strengths is shown in Fig. 8. Compared with Fig. 6, the grey value changes obviously when the MO solution becomes transparent. The degradation of MO turns out to be obvious as the UV light intensity increase from 0 to 3 W/m², and it was also proved that the ultraviolet energy should be required during photocatalysis.
From the photographs presented in Fig. 6, it could be noticed that MO degraded more with the increase in UV exposure time at constant UV intensity. Of course, MO degradation occurs in the form of reduction in total mass of MO solution. For the samples under the UV light, the photocatalysing was distinct. The sample under the higher UV light intensity could degrade MO more rapidly through the total mass change as presented in Fig. 9. The MO on the sample surface under a UV strength of 3 W/m² degraded quickly and the MO disappeared completely by a chemical reaction before 120 min.

3.2 Influence of electric field strength

In the experiments about the influence of electric field to photocatalysis, MO solution was set as 0.3 g, 90 mg/L, so that the phenomenon of colour changes could be observed more clearly. Fig. 10 exhibits the photograph results of three samples with the applied electric field of 0, 2.13 and 8.52 kV/cm. The UV strength was kept 3 W/m² for each sample. The MO solution would degraded under all electric field strength because of the existence of UV light. Comparing Fig. 10a with Figs. 10b and c, the influence of electric field on photocatalysis is obvious.

As can be seen in Fig. 10, the degradation effect of photocatalysis was more distinct with the presence of electric field (shown in Figs. 10b and c) than that without the action of electric field (shown in Fig. 10a). Figs. 11 and 12 present the grey value and the variation of total mass change for the samples under different electric fields, respectively, it is apparent that the photocatalysis process could be well promoted by suitable applied electric field.

4 Theoretical model and analysis

4.1 Equations for the simulation

The theoretical simulation of this investigation is based on the law of mass action. The reaction rate is proportional to the effective mass of reactant

$$\frac{d[A]}{dt} = \frac{k_f}{k_r} \prod_{i \in \text{react}} c_i^{v_i} - \frac{k_f}{k_r} \prod_{i \in \text{prod}} c_i^{v_i}$$

where $r_j$ refers to the reaction rate, $c_i$ is the concentration of the matter, $v_i$ is the stoichiometric number. The quantity of the reactant is usual no more than two. There are various reactions between different substances. The forward reaction is dominant for most reactions in the simulation.
\[ \frac{\partial c_i}{\partial t} + \nabla \cdot (-D_i \nabla c_i) = r_i \] (4)

\[ N_i \] \((i = 1, 2, 3, 4)\) is the net flux at the boundary. In the process of simulation, the flux of boundary is 0 then \( N_i = 0 \) (Fig. 13). The reaction happened in the inner region and the substances does not diffuse outward [41]. Equation (4) is the diffusion equation combined with concentration change. \( c_i \) is the concentration for different species. \( D_i \) is the diffusion coefficient for different species. \( r_i \) is the change rate over time for different species [42, 43].

Photocatalysis process takes the advantage of photocatalytic functional material having a narrow forbidden band to produce oxidising substance [44]. The reaction equations in the reaction process are shown in Table 2. Reaction 1, (5) is the process of the generation of electron–hole pairs by TiO\(_2\) under the UV light. The life time of pairs is very short and the electron and hole are easy to recombine as is shown by reaction 2, (6) [45]. Reaction 3, (7) and reaction 4, (8) are the processes of the generation of strong oxidising substance and the oxidation of organics respectively.

The strength of UV light is considered to be the main influence to the generation of electron–hole pairs in this investigation. \( \Phi_{\text{TiO}_2} \) is the quantum yield for TiO\(_2\) to generate electron–hole pairs [47], \( I_a \) is the strength of UV light, \( V \) is the volume of the organic contamination, \( k_i \) \((i = 1, 2, 3, 4)\) is the reaction rate corresponding to the different reactions. Square brackets mean the concentration of the substance [48, 49]. Catalyst and water are constant in the simulation. Both the concentration of electron and the concentration of hole are \(10^{-6} \text{ mol/m}^3\) in the initial time.

In the simulation, the following assumptions were made:
(i) Reaction 3 happened quickly that means little part of the hole generated from reaction 1 would recombine with electron. Most of the hole would join reaction 4 to generate hydroxyl radical (\(\cdot\)OH).

(ii) The forward reaction 3 played a dominant role, thus, the counter reaction of reaction 3 was ignored.

The equilibrium equations could be obtained through reaction rates and chemical reactions, the equilibrium equations for each matter are present as (9)–(13) in Table 3.

### 4.2 Results of the simulation

The initial substances were TiO\(_2\), MO and water in the simulation, the setup of MO solution was the same as those in the experiments. The main influence factors were illumination intensity and electric field. Six different levels of UV intensities and eight different levels of electric field strengths were computed in this work, the results are displayed in Fig. 14.

Simulation and experimental results of the concentration of MO under different UV strengths are compared in Fig. 15. With the change of exposure time, the reaction rate for each sample decreased gradually. The concentration of MO was decreased with the oxidation of MO that also could be concluded from reaction 4, (8). The transition of electron requires luminous energy in the process of photocatalytic process. The energy requirement of transition becomes lower if the forbidden band between valence band and conduction band is narrower. TiO\(_2\) has short forbidden band that enhances the transition probability of electron. With the increase of UV intensity, the electron can obtain more photon energy to across forbidden band and then leave the hole. The hole

### Table 2 Reaction network [46]

| Reaction rate | Reaction                                                   | Rate equation                                                                 |
|---------------|------------------------------------------------------------|--------------------------------------------------------------------------------|
| \(r_1\)      | \(\text{TiO}_2 \rightarrow \text{e}^-_{cb} + h^+_{vb}\) | \(r_1 = k_1 \cdot [\text{TiO}_2] = \frac{\Phi_{\text{TiO}_2} \cdot I_a}{V}\) (5) |
| \(r_2\)      | \(\text{e}^-_{cb} + h^+_{vb} \rightarrow \text{heat}\)   | \(r_2 = k_2 \cdot [\text{e}^-_{cb}] \cdot [h^+_{vb}]\) (6)                     |
| \(r_3\)      | \(h^+_{vb} + \text{H}_2\text{O} \leftrightarrow \cdot\text{OH} + \text{H}^+\) | \(r_3 = k_3 \cdot [h^+_{vb}] \cdot [\text{H}_2\text{O}]\) (7)                 |
| \(r_4\)      | \(\cdot\text{OH} + \text{org} \rightarrow \text{CO}_2 + \text{H}_2\text{O}\) | \(r_4 = k_4 \cdot [\cdot\text{OH}] \cdot [\text{MO}]\) (8)                     |

### Table 3 Mass balance equations in the simulation

| Mass balance equations | Species               | |
|------------------------|-----------------------||
| \(\frac{d[e^-_{cb}]}{dt}\) | electrons             | (9) |
| \(\frac{d[h^+_{vb}]}{dt}\) | holes                 | (10)|
| \(\frac{d[\text{H}_2\text{O}]}{dt}\) | water                 | (11)|
| \(\frac{d[\cdot\text{OH}]}{dt}\) | hydroxyl radical      | (12)|
| \(\frac{d[\text{MO}]}{dt}\) | methyl orange          | (13)|

![Simulation results of the samples under different UV light strength or electric field strength](image-url)
reacts with water to generate hydroxyl radical which is strong oxidising. As hydroxyl radical is an important substance to degrade organic matter, hence, with the development of UV intensity, photocatalytic material TiO$_2$ can generate more electron–hole pairs to oxidise organic matter.

In Fig. 16, $e^-$ and $\gamma$ are electron and photon, respectively, $h$ is Planck constant, $v$ is the frequency of the light, $E_{\text{pho}}$ is the energy of a photon, $E_{\text{tran}}$ is the energy for the transition of electron, $n_{\text{pho}}$ is the amount of the photon, and $I$ is the light intensity. When the energy of photons is enough to satisfy the electron transition, the electron can be excited to transit to the conduction band as shown in Fig. 16. The energy of photons is in proportion to the frequency. So the transition of electron will be more likely to occur under the ultraviolet light. The energy of photon is also in proportion to the light intensity with the light in a certain wavelength range. The amount of photon is higher with the increase of light intensity. Then more electrons will be excited and the transition probability increases [50].

$$E_{\text{pho}} \geq E_{\text{tran}}$$  \hspace{1cm} (14)  
$$E_{\text{pho}} = hv$$  \hspace{1cm} (15)  
$$n_{\text{pho}} \propto I$$  \hspace{1cm} (16)

The dynamic motions of electron and hole under auxiliary electric field could be expressed by (17) and (18)

$$\frac{d^2s_{ho}}{dt^2} = \frac{4\pi^2q_{ho}EdW_{ho}}{h^2} \frac{dk^2}{dE_{\text{tran}}}$$  \hspace{1cm} (17)

$$\frac{d^2s_e}{dt^2} = -\frac{4\pi^2eEdW_e}{h^2} \frac{dk^2}{dE_{\text{tran}}}$$  \hspace{1cm} (18)

where $ho$ and $e$ refer to hole and electron, respectively, $E$ is the auxiliary electric field strength, $s_{ho}$ and $s_e$ are the displacement, $W_{ho}$ and $W_e$ are the energy of hole and electron, respectively, $h$ is Planck constant, and $k$ is the wave vector.

According to (17) and (18), the auxiliary electric field could separate electron and hole, at the same time, the recombination of electron and hole could be restrained that will increase the productive rate of hole [51]. The calculated number of hole under different electric field and 3 W/m$^2$ UV strength is shown in Fig. 17. It is clear that with the increase of electric field, more Electron and hole may move in the opposite direction as shown in Fig. 18, therefore, more hole could be utilised in reaction 2, (6), which could make remarkably contribution to the reaction 3 process in the forward direction, consequently, more hydroxyl radical will be produced to degrade MO.

Therefore, it could be observed in Fig. 19a that more MO could be degraded over time as the electric field increases from 0 to 8.52 kV/cm. The maximum deviation can reach 16% in the beginning. However, the variation trend of calculation results is in accord with the experiment. With the increase of time and field strength, the error decreases gradually to 5%. With the increase it could also be noticed in Fig. 19b that the gradient of the curves changes slowly as the electric field exceeds 6 kV/cm, hence, the electric field-activated effect might be saturated if it is above 6 kV/cm.

5 Conclusions

A TiO$_2$ coat on the surface of a conductor indicated photocatalysis effect by removing MO, an organic substance, from the conductor surface. The photo-catalytic effect was achieved by producing electron–hole pairs due to the influence of UV. The hole can react with moisture to produce hydroxyl radical that can oxidise MO to lead its degradation.

The degradation of MO becomes more pronounced when the intensity of UV is increased to produce more electron–hole pairs.
In this experimental study it was observed that, MO degraded more quickly with high UV intensity with lighter colour than the low UV intensity for the same reaction time. The auxiliary electric field could also promote the degradation of MO. The promotion of electric field to photocatalysis was better with the increase of electric field; however, the electric field-activated effect might be saturated if it is above 6 kV/cm.

This experimental phenomenon was also explained by theoretical simulation. The increase of UV intensity promoted TiO$_2$ convert light energy into chemical energy to generate more electron–hole pairs, which would accelerate the degradation of MO. With the auxiliary electric field, the recombination of electron and hole could be restrained that would increase the productive rate of hole; therefore, more hydroxyl radical would be produced to degrade MO.

The further improvement of photocatalytic materials in order to degrade typical inorganic contaminants would also be of great value to outdoor electric power equipment, but this was outside the scope of the present paper and it would be reported in the future research work.
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7 References

[1] Schneider, T., Holst, E.: ‘Variability of total mass and other measures of small particles of’, J. Aerosol Sci., 1995, 26, (1), pp. 127–136
[2] Mei, H., Guan, X., Fu, X., et al.: ‘Influence of tower anticorrosion coating as contaminant on operation characteristics of composite insulator’, High Volt., 2018, 3 (3), pp. 193–198
[3] Cheng, L., Zhao, S., Zhang, S., et al.: ‘Research on the long-time operation performance of composite insulator shield hydroprophobic under hydrothermal conditions’, High Volt., 2018, 3 (3), pp. 67–72
[4] Jiang, X., Yuan, J., Shu, L., et al.: ‘Comparison of DC pollution flashover performances of various types of porcelain, glass, and composite insulators’, IEEE Trans. Power Deliv., 2008, 23 (2), pp. 1183–1190
[5] Zang, Z., Qiao, X., Zhang, Y., et al.: ‘AC flashover performance of different shed configurations of composite insulators under fan-shaped non-uniform pollution’, High Volt., 2018, 3 (3), pp. 199–206
[6] Majid Hussain, M., Farokhi, S., McMeekin, S.G.: ‘The role of oxygen and reaction intermediates in the photocatalytic activity of TiO2 film: the combination of Ag deposition with application of external electric field’, Thin Solid Films, 2018, 638, pp. 25–31
[7] Vinodgopal, K., Stafford, U., Gray, K.A.: ‘The role of oxygen and reaction intermediates in the photocatalytic degradation of TiO2 catalyst prepared by microwave solvothermal method’, J. Phys. Chem. C, 2006, 110 (19), pp. 8399–8404
[8] Gonzalez, R.C., Woods, R.E.: ‘Digital image processing’, 3rd edn., Prentice Hall, Upper Saddle River, NJ, 2004
[9] Tang, J., Zou, Y., Ye, J.: ‘Efficient photocatalysis on BaBiO3 driven by visible light’, Chem. Commun., 2013, (32), pp. 1184–1186
[10] Honda, K., Fujishima, A.: ‘Electrochemical photolysis of water at a titanium electrode’, J. Electroanal. Chem., 1972, 38, (3), pp. 217–218
[11] Mills, A., Lee, S., Lepre, A.: ‘Photodecomposition of ozone sensitised by a semiconductor’, Surf. Sci. Catal., 2001, (2), pp. 120–127
[12] Honda, K., Fujishima, A.: ‘Photocatalytic degradation of TiO2 for efficient electron–hole separation and high solar-driven hydrogen permeation through ferritic steel and amorphous Fe40Ni40Mo4B16 alloy specimens’, J. Nucl. Mater., 2018, 495, pp. 988–995
[13] Gonzalez, R.C., Woods, R.E.: ‘Digital image processing’, Prentice Hall, New York, 2008
[14] Georgeris, J.S., Anestis, L.A.: ‘Influence of the surface processes on the hydrogen permeation through ferritic steel and amorphous Fe40Ni40Mo4B16 alloy specimens’, J. Nucl. Mater., 1997, 249 (2), pp. 133–141
[15] Leaist, D.G.: ‘Diffusion with stepwise aggregation in aqueous solutions of the ionic dye methyl orange’, J. Phys. Chem. Lett., 2013, 14, (3), pp. 332–341
[16] Tang, J., Zou, Y., Ye, J.: ‘Efficient photocatalysis on BaBiO3 driven by visible light’, J. Phys. Chem. C, 2007, 111 (34), pp. 12779–12785
[17] Kesselman, J.M., Lewis, N.S., Hoffmann, M.R.: ‘Photoelectrochemical degradation of Humic Acid under sun simulated light on TiO2’, J. Phys. Chem. Lett., 2019, 10 (28), pp. 120–127
[18] Macle, G., Wadhawan, J., Compton, R.: ‘Photocatalytic reduction of chlorinated nitrobenzenes: heavy atom versus radical ion lifetime effects’, J. Electroanal. Chem., 2003, 510 (1), pp. 120–127
[19] Håkkelung, S.A., Balle, K., Høiland, B.: ‘Influence of tower anticorrosion coating as contaminant on operation characteristics of composite insulator shield hydroprophobic under hydrothermal conditions’, High Volt., 2018, 3 (3), pp. 67–72
[20] Li, D., Zheng, Y., Fu, X., et al.: ‘SO2−4/TiO2 catalyst prepared by microwave solvothermal method as a dye-sensitized solar cell’, J. Photochem. Photobiol. A, 2009, 201 (2), pp. 151–157
[21] Rabe, H.F., Bhatia, A., Steigerwald, R.A.: ‘Application of carbon aerogel electrosorption for enhanced Bi2Wg photocatalytical reduction and elimination of trace noryl nonylphenol’, Carbon, 2012, 86, pp. 279–288
[22] Dai, B., Liu, C., Kou, J., et al.: ‘Photocatalytic performance of PMN-PT TiO2 highly enhanced by alternative spatial electric field induced charge separation effect’, J. Alloys Compd., 2017, 696, pp. 988–995
[23] Phan, D.D., Babick, F., Triph, J.H.T.: ‘Investigation of fixed-bed photocatalytic membrane reactors based on submerged ceramic membranes’, Chem. Eng. Sci., 2018, 191, pp. 332–342
[24] Vinodgopal, K., Stafford, U., Gray, K.A.: ‘The role of oxygen and reaction intermediates in the photocatalytic degradation of 4-chlorophenol on TiO2 particulate films’, J. Phys. Chem., 1994, 98, p. 6797
[25] Hidaka, H., Ajayka, K., Horiuchi, S., et al.: ‘Comparative assessment of the efficiency of TiO2/OTE thin film electrodes fabricated by three deposition methods: photoelectrochemical degradation of the DAB anionic surfactant’, J. Photochem. Photobiol. A, 2001, 138 (2), pp. 185–192
[26] Fan, Z. Shi, H., Li, X., et al.: ‘Effect of carbon aerogel electrosorption for enhanced Bi2Wg photocatalytical reduction and elimination of trace noryl nonylphenol’, Carbon, 2012, 86, pp. 279–288
[27] Torres, R.A., Nieto, J.J., Combet, E., et al.: ‘Influence of TiO2 concentration on the synergistic effect between photocatalysis and high-frequency ultrasonic for organic pollutant mineralization in water’, Appl. Catal. B, 2008, 80 (1), pp. 168–175
[28] Sun, X., Luo, W., Chen, L., et al.: ‘Synthesis of porous al doped ZnO nanosheets with high adsorption and photocatalytic activity and the key role of al doping for methyl orange removal’, RSC Adv., 2016, 6, pp. 2241–2251
[29] Oldershaw, R.L.: ‘Rydberg atoms, variable stars, Kepler’s third law and E = hv’, Int. J. Gen. Syst., 1988, 14 (1), pp. 77–84
[30] Xu, Y., Zhong, D., Jia, J., et al.: ‘Dual plasnt-emplaced electrodes thin-film photocatalytic reactor: enhanced dye degradation efficiency by self-generated electric field’, Chem. Eng. J., 2013, 225, pp. 138–143

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