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Exploration of a MgO cathode for improving the intensity of pulsed discharge plasma at atmosphere

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Abstract
With regard to the lower density and energy of electrons in pulsed discharge plasma (PDP) at atmosphere, leading to the lower energy utilization of plasma, we propose a MgO cathode to enhance the plasma intensity according to field emission principle. The MgO cathode is prepared by an electro-depositing MgO film on a stainless steel plate. This way, the positive charges come to the cathode and accumulate on the surface of the MgO film, leading to the enhancement of the electric field intensity between the cathode and MgO film, and result in the strong emission of secondary electrons from the MgO cathode. As a result, the intensity of plasma can be enhanced. Herein, the effect of the MgO cathode on the intensity of PDP is investigated. It was shown that the discharge peak current was improved by 20% compared with that of without the MgO cathode. With increasing the MgO film thickness, discharge intensity, including the peak current, transforming charge and spectrum intensity first increased and then decreased. Higher enhancement of peak current, transforming charge and spectrum intensity were acquired with a higher peak voltage. Compared to a cathode without MgO film, the ozone production is higher with MgO cathode employed. The research proposes a novel approach for improving the intensity of discharge plasma, and also provides a reference for further application of PDP.

Keywords: discharge intensity, pulsed discharge plasma, MgO cathode, secondary electron emission

(Some figures may appear in colour only in the online journal)

1. Introduction

In recent decades, atmospheric-pressure pulsed discharge plasma (PDP) has been widely utilized for waste gas treatment, such as SO2, NOx, Hg, etc [1–3]. The mechanism is summarized as the ionization and excitation process produced from the collision between high-energy electron and neutral gas molecules, inducing the chain reaction of the electron, ion and molecule. The reaction makes for the generation of active specials which has higher oxidation potential, such as -OH, O3, +O, etc. The generated active specials then react with the contaminant molecule, resulting in the transformation from toxic substance to innoxious substance or lower toxic substances. However, in the practical application, the generated electron density and energy are relatively lower, which has restricted the development of PDP. The essential issue of PDP for waste gas treatment, therefore, is how to acquire higher electron density and higher electron energy of plasma.

In order to improve the intensity of plasma and ionization area between the electrodes, it is essential to be provided with
adequate seed electrons to induce more electron avalanche
and then enhance the amount of discharge streamer-channels.
According to the principle of self-sustained discharge [4, 5],
the discharge can be maintained by the seed electrons gen-
erated from the cathode process on the condition of no heat,
light and radioactive sources. The cathode process includes:
(1) the bombardment of the positive ion on the cathode
(γ process) which is used to produce the seed electrons; (2) the
act of photon irradiation and metastable particles generated
discharge on the cathode. Dong et al [6] have researched
the electric field distribution of PDP with line-plate electrode,
and found that the electric field intensity around the cathode
is a tenth less than that around the line. It can be seen that
the cathode process is relative lower. It is therefore necessary
to develop a method for improving capacity of electron release
from the cathode, and then enhance the amount of seed
electrons inducing the atmospheric discharge. Based on this,
the generation efﬁciency of active specials produced by
plasma discharge is improved and then leads to the efﬁcient
application of PDP ultimately.

Field emission is one of methods for producing seed
electrons at low atmosphere [7, 8]. When the oxide is covered
in the surface of cathode, the positive charges are accumu-
lated on the surface of the oxide, inducing the generation of
high intensity electric ﬁelds (>10⁷ V m⁻¹) between the oxide
layer and the cathode. The process promotes the conduction
electron to overcome the potential barrier of the cathode and
then release from the surface of the cathode to the surface of
the oxide. One part of the released electron is utilized to
neutralize the positive charge on the surface of oxide, and the
others are used as the seed electrons for promoting the dis-
charge. The phenomenon is named as the Malter effect, which
was ﬁrst discovered by Malter in 1936 [9–13]. Therefore, it
can be found that a certain intensity electron ﬁeld is essential
to generate the Malter effect.

MgO is a solid electrical insulating material with a cubic
crystal structure, which has a high secondary electron emis-
sion coefﬁcient, great tolerance for ion bombardment and
high stability [14–18]. As a secondary electron emission emitter, MgO has been widely used in plasma display panels
and some other electronic devices [19–24]. As a dielectric
protection layer of plasma display panels, MgO is not
only able to resist ion bombardment and extend the working
life of plasma display panel, but it is also able to decrease the
firing voltage and maintain voltage of gas discharge, which
enhances its light intensity and decreases the power con-
sumption of plasma display panels. So far, MgO is conﬁned
to apply in electron multiplier as a secondary electron emis-
sion emitter. To the best of our knowledge, few researchers,
however, have adopted the secondary electron emission
property of MgO for enhancing the discharge intensity of
plasma. Herein, we ﬁrst propose the use of MgO ﬁlm to
embellish the cathode (named MgO cathode) for enhancing
the ﬁeld strength of the cathode and then improving the
density of pulsed discharge plasma (PDP). In the paper, the
effect of the MgO cathode on the intensity of PDP is inves-
tigated according to different perspectives, including peak
current, transforming charge, spectrum intensity, apparent
statue and ozone production. The research proposes a novel
approach to enhance the performance properties of PDP and
can also be expected to provide reference for the scientiﬁc
researches related to discharge plasma.

2. Experimental

2.1. Material

The MgO ﬁlm used in the study was prepared on a stainless
steel plate with the electrolytic deposition method. The dia-
meter and thickness of the stainless steel plate are 50 mm and
1 mm, respectively. Before electrolytic deposition, the stain-
less steel plate was ﬁrst dipped in acetone to remove the oil
stain, and then was dipped in ethanol to remove surface
organic compounds; and third was rinsed in distilled water
and ultrasound for 5 min; and last was dried in an oven before
electrolytic deposition. The voltage of electrolytic deposition
was set as 45 V, and the gap of the anode and cathode is
10 mm. The deposited MgO ﬁlm was calcined in a muffle
with 700 °C annealing temperature for 120 min. Before the
experiment, the calcined stainless steel plate with MgO ﬁlm
was ﬁxed in the reactor as the cathode.
3.3 Results and discussion

3.1. Characteristic of MgO film

The apparent morphology of the prepared MgO film sample is shown in figure 3(a), which elucidates that MgO film adheres to the stainless plate successfully. The XRD patterns for the MgO samples before calcination and after calcination and after discharge are given in figure 3(b). It can be seen that there are two main diffraction peaks in the three samples appearing at $2\theta = 42.86^\circ$ and $2\theta = 62.22^\circ$ which are (200) orientation and (220) orientation respectively. There is no obvious variation of the MgO crystal among the three samples, indicating that the calcination and discharge are not able to alter the crystal structure of MgO. Meanwhile, the granularity of the three samples is also calculated by Scherrer Formula, which shows that granularity of 52.4 nm, 57.6 nm and 54.5 nm appear in the MgO samples before calcination and after calcination and after discharge, respectively. Also, no clear variation of the granularity exists in the three samples. Thus, it can be concluded that the MgO film has stable crystal structure, which can overcome high temperature and electron bombardment and suitable applications for field emission. The figures 3(c) and (d) represent the morphological of the MgO film surface annealed at 700 °C, which deduces that an ideal MgO film can be obtained by the electrolytic deposition. The further enlarged morphological manifests the MgO film is actually a ceramic membrane aggregated and sintered by nanometer MgO [25].

3.2. Application of MgO film in PDP system

The feasible of MgO cathode for enhancing the intensity of PDP is first investigated. The gas ambience is on the air condition at atmospheric pressure, which is kept consistent in following experiment. The peak voltage, pulsed frequency and electrode gap are set uniformly as 12 kV, 50 Hz and 5.5 mm, respectively. The MgO film thickness is controlled as 5.90 μm. The current waveform with or without the MgO cathode is shown in figure 4(a).

It can be seen that when the MgO cathode was explored, the current enhanced clearly compared to non-existence of MgO cathode. The peak current varies from 4.0 A to 4.6 A, indicating that the current is enhanced by 15% when exploring the MgO cathode. Figure 4(b) represents that enhancement of power reaches 0.26 W with the MgO cathode, which is 16.3% higher than that without the MgO cathode. The enhancement mechanism is summarized as follows: when ample pulsed voltage is applied between the high-voltage electrode and ground electrode, the gas is ionized with the generation of positive charge and electrode. The positive charges are moved from the anode electrode to the cathode and after discharge are given in figure 3(b). It can be seen that there are two main diffraction peaks in the three samples appearing at $2\theta = 42.86^\circ$ and $2\theta = 62.22^\circ$ which are (200) orientation and (220) orientation respectively. There is no obvious variation of the MgO crystal among the three samples, indicating that the calcination and discharge are not able to alter the crystal structure of MgO. Meanwhile, the granularity of the three samples is also calculated by Scherrer Formula, which shows that granularity of 52.4 nm, 57.6 nm and 54.5 nm appear in the MgO samples before calcination and after calcination and after discharge, respectively. Also, no clear variation of the granularity exists in the three samples. Thus, it can be concluded that the MgO film has stable crystal structure, which can overcome high temperature and electron bombardment and suitable applications for field emission. The figures 3(c) and (d) represent the morphological of the MgO film surface annealed at 700 °C, which deduces that an ideal MgO film can be obtained by the electrolytic deposition. The further enlarged morphological manifests the MgO film is actually a ceramic membrane aggregated and sintered by nanometer MgO [25].

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surface barrier and release from the MgO layer due to the work function, which is namely the secondary electron. Due to the existence of secondary electron, the discharge intensity enhances and attributes to the higher peak current. The schematic illustration of electron transfer is summarized in figure 5. The process of electron enhancement is consistent with the $\gamma$ process of Townsend discharge theory [26]. Therefore, it is concluded that the application of MgO cathode for the enhancement of discharge intensity is feasible.

3.3. Effect of MgO film thickness on discharge intensity

The MgO film thickness is determined by the coating time. In this section, the thickness of 5.9 $\mu$m, 11.60 $\mu$m, 14.95 $\mu$m and
20.78 μm with coating time of 20 s, 40 s, 60 s and 80 s respectively on discharge intensity are investigated. The peak voltage and electrode gap are set uniformly as 12 kV and 5.5 mm, respectively. The results are shown in figure 6(a). In order to declare the effect of MgO film thickness on discharge characteristic clearly, the peak current and transforming charge are calculated, which are shown in figure 6(b). Besides, the emission spectrum intensity under different MgO film thicknesses is also investigated to account for the variation of discharge intensity, shown in figures 6(c) and (d).

From figures 6(a) and (b), we can see that with the increase of MgO film thickness, the peak current increases first and then decreases. The highest peak current can reach 4.8 A when the MgO film thickness is 11.60 μm. The peak voltage increases from 4.0 A to 4.8 A and then decreases to 4.6 A. The highest peak current is 20% higher than that without the MgO cathode. It can be seen from figure 6(b) that the change trend of transforming charge is consistent with the result of figure 6(a). The highest transforming charge is obtained with the MgO film thickness of 11.60 μm, which reaches 453 nC approximately. From figure 6(c), it can be seen that the emission spectrum mainly focuses on the second positive band of N2 (C^+[Ia] → B^+[Ib]) [27]. The highest emission intensity appeared at the wavelength of 357.8 nm. Correspondingly, the intensity of emission spectrum enhances first and then decreases with the increase of MgO film thickness, which is varied clearly by spectrum intensity at the wavelength of 357.8 nm (shown in figure 6(d)) and the result is in agreement with the result of peak current and transforming charge. The reason can be included as follows: with the increase of the MgO film thickness in the preliminary stage, more secondary electrons are activated by electric field formed by charge accumulation in the cathode since the electrons in MgO film can overcome the surface barrier and release from the MgO layer. However, when the thickness of MgO exceeds a certain constant, on one hand, electrons at the bottom of MgO layer need to overcome more energy and then release the MgO layer, which leads to the decline of runaway electrons; on the other hand, the higher MgO film thickness leads to the lower electric field intensity according to the formula of U/d, when electric field intensity is lower than the work function of MgO, it is unable to release the secondary electrons. As a result, the discharge intensity became weak when the MgO film thickness exceeds 11.60 μm. Therefore, the MgO film thickness is in keeping with 11.60 μm in the following experiment.

3.4. Effect of peak voltages on discharge intensity

As presented in figure 7(a), with the increase of peak voltage, the peak current enhances no matter with or without the MgO cathode. Compared to the non-existence of MgO cathode, the peak current improves under the three peak voltages, which illustrates that the MgO cathode is benefit for the enhancement of discharge intensity. The figure 7(b) shows the variation of transforming charge under different peak voltages with and without the MgO cathode. It can be seen that when the MgO cathode is applied, the transforming charge increases. Moreover, the enhancement of transforming charge increases with the increase of peak voltage, approximately 27.6 nC, 31.1 nC and 63.4 nC are enhanced under the peak voltages of 11 kV, 12 kV and 13 kV, respectively. The reason is concluded that the higher peak voltage leads to the stronger discharge intensity, which then induces more charges to be accumulate on the surface of MgO film. Consequently, the generated electron field between the surface of the MgO film and cathode becomes higher, inducing more secondary electrons in the MgO film to overcome the work function and release into the discharge channel.

In order to illustrate the variation of discharge status more intuitively, the typical discharge images with 12 kV peak voltage are given in the figure 8. It can be found that when the MgO cathode is explored, the light intensity of discharge becomes stronger. The gray value of the discharge image under different peak voltage is calculated and shown in figure 9. The enhancements of gray values are 1.963, 2.0043 and 4.7081 with peak voltages of 11 kV, 12 kV and 13 kV, respectively, which is consistent with the result of discharge current and transforming charge. Therefore, it can be seen that the feasibility of MgO cathode for improving the intensity of PDP is also proved by the optical intensity.

More electrons can be generated when the MgO cathode is applied, which induces more gas molecules to collide with the electrons and then leads to the production of electron avalanche. Afterwards, high-energy electrons, ions and free radicals are generated, and a lot of them are recombined to produce ozone, which can be produced by the following procedure [28, 29]:

\[ e^- + O_2 \rightarrow 2O + e^- \]  
(3)

\[ O + O_2 + M \rightarrow O_3 + M (M = O, O_2, O_3 \text{ and } N_2) \]  
(4)
Figure 6. The effect of coating time on discharge intensity: (a) current waveform, (b) peak current and transforming charge, (c) emission spectrum, (d) spectrum intensity at the wavelength of 357.8 nm.

Figure 7. Effect of peak voltage on discharge intensity: (a) current waveform; (b) transforming charge.
Therefore, the production of ozone with and without the MgO cathode is investigated in the study. As shown in figure 10, with the increase of peak voltage, the concentration of ozone increases. The highest concentration is obtained when 12 kV peak voltage is applied with MgO cathode, which reaches 0.058 mg L\(^{-1}\). When the MgO cathode is applied, the increment of ozone production is attributed to strengthen of discharge intensity. Approximately 0.005 mg L\(^{-1}\), 0.008 mg L\(^{-1}\) and 0.016 mg L\(^{-1}\) ozone concentrations can be improved when MgO cathode is adopted with the peak voltages of 11 kV, 12 kV and 13 kV, respectively. Therefore, it can be seen that the feasibility of MgO cathode for improving the intensity of PDP can be also testified by the generation of active special. Moreover, it is deduced that the application of the MgO cathode can be employed to enhance the treatment efficiency of exhausted gas.

4. Conclusion

In the paper, a MgO cathode was adopted for improving the intensity of PDP. The MgO film was first prepared by the electrolytic deposition method and characterized with XRD and SEM. The effect of the MgO cathode on discharge intensity, including peak current, transforming charge, spectrum intensity, apparent statue and ozone production, was then investigated. The result showed that MgO film had a stable crystal structure after calcination and discharge. The application of the MgO cathode could improve the discharge intensity evidently. The higher discharge intensity was obtained with the MgO film of 11.60 μm. With the increase of peak voltage, the enhancement of the peak current, transforming charge, gray value and ozone production all raised. The feasibility of the MgO cathode for improving the intensity of PDP has been demonstrated based on physical and chemical properties. The study proposes a novel method for enhancing the intensity of plasma and improving the energy utilization of waste gas treatment in the future.

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References

[28] Yao S L et al 2015 J. Electrostat. 75 35