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Experimental Study on Gas Evolution Characteristics of DC Deep Well Grounding Electrodes

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ABSTRACT Deep well grounding electrodes (DWGE) have small occupied areas. The number of sub-ground electrodes is less than that of traditional vertical grounding electrodes. Thus, the former has a favorable development prospect. However, given that the active part of a DWGE is buried in the deep earth, DWGE faces more complex gas exhaust problem than shallow-buried grounding electrodes. To research the gas evolution characteristics of DWGE, a U-shaped gas evolution experimental platform that can collect anode and cathode gases separately is designed. Carbon steel material is used as the electrode, and experiments have been conducted on water and saturated coke on the basis of the designed platform and a 30-m DWGE test. The results show that the operating environment and mode (anodic/cathodic) affect gas evolution. When inside water, only the reaction of Fe dissolution occurs at the anode, and Fe is transformed into Fe^{2+} while hydrogen evolution and oxygen consumption reactions occur simultaneously at the cathode. When in saturated coke, the gas production at the cathode increases with ampere-hours, thereby changing the contact resistance between the electrode and the coke and forming a “bubble resistance”, then leading to a gas block. The test result of a 30 m well at 100 A further verifies the experimental results of the designed platform and confirms that a vent pipe plays a role in practical use.

INDEX TERMS Deep well grounding electrode, electrode reaction, gas evolution characteristic, gas block.

I. INTRODUCTION

Earth electrodes play essential roles in high-voltage direct current (HVDC) transmission projects. When the HVDC system works in monopole configurations with a continuous earth operation or a fault causes bipolar configuration that transforms into a monopolar ground return mode, numerous amperes of working current will be fed into earth. For economic considerations, in most HVDC projects, a ground return path, rather than a metallic return path, is typically used for short-time transmission [1], [2]. Large-scale shallow horizontal electrodes or vertical electrodes with numbers of parallel sub-electrodes are commonly used to satisfy the requirements of low step voltage and ground resistance [3]. Generally, a considerable area of land will be needed

(e.g., circumference of a horizontal ring electrode can reach 3km) [4]. Economic and social issues due to land expropriation policy and a shortage of land resources limit site selection [5]. Thus, it is necessary to seek an economic and applicable HVDC electrode scheme [6]–[8].

Deep well grounding electrode (DWGE) is a kind of vertical electrode; it uses the depth of 100–1000 m of earth to reach a deep but low resistivity layer [9]; moreover, a single or a few sub-electrodes can satisfy the technology requirements and cover a smaller area than the traditional grounding electrode, thus significantly reducing land use and simplifying site selection [10]. When DC is impressed to the electrodes, electrochemical reactions occur at the interface between a metal and an electrolyte (e.g., underground water, saturated soil, and coke), and then gas will be generated. Due to the end effect of the current distribution, the DWGE produces large amount gases at the end of the electrode.

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In addition, the DWGE faces more difficult gas release problem than the traditional horizontal land electrode or the sea electrode whose gas can be carried away by the ocean current movement, given the deeply buried depth of the DWGE. Such gases commonly evolve and migrate to the periphery of the electrode. If the excess gas cannot be relieved effectively, then it may increase earthing resistance, which can be called “bubble resistance”, to cause thermal instability. Several 100 m-deep anodes in cathodic protection projects have been scrapped due to the gas block, whose working principle is similar to the HVDC electrode.

In terms of applying deep well electrode research, an experimental deep hole electrode has been installed in a Swedish converter station in the Baltic Cable project [11]. However, no literature on this experiment has been published, and no similar deep electrode project has been applied. The characteristics of electrodes being electrolyzed to produce hydrogen from seawater were studied by Bennett J.E. in 1980; this researcher emphasized that two anodic competing reactions can occur, and Cl_2 and O_2 can be evolved, chlorine productivity could be determined through iodimetry titration [12]. The gas productivity of the Baltic HVDC sea electrode was calculated by Tykeson K and Nyman A using Faraday formula, which showed that H_2 and OH^- can be evolved in the cathodic reaction, and the competitive ratio of oxygen and chlorine evolved from the anode is related to the Mixed Metal Oxide (MMO) material coating [13], [14]. The CIGRE guideline points out that the annual production rate of Cl_2 and O_2 is 327 mol/A•year at the anode of a titanium grid in the Baltic HVDC project [10].

The electrochemical reaction process and conductive mechanism vary with different electrolytes, such as sea water, saturated soil, and coke. In addition, the gas evolved in seawater can be easily diffused through the ocean current [15], whereas the bubble resistance in the land electrode will be formed through the accumulation effect under earth. Thus, the existing conclusion of sea electrode gas evolution cannot be completely applied to the land electrode. Although the influence of bubble evolving behavior on circuit resistance has been studied by many scholars in the field of electrochemical galvanic cell [16], [17], the behavior is generally used for industrial applications, such as aluminum production, and the electrolytic cells are generally composed of two parallel panel electrodes, whose current path and electrode reaction process are different from the DWGE [16], [18], [19]. In deep anode systems for cathodic protection, the gas that accumulates in the well can be released by installing a vent pipe [2], [20], but detailed research on the characteristics of gas production remains lacking. Therefore, when a high current is injected into earth, the kind of reactions that occur in the vicinity of different electrodes, whether competitive reactions exist, and if the gas block effect has a critical point of current density, is unclear.

Given all that, a mature theory on characteristic of gas evolution of land electrode has not been established. Therefore, using carbon steel electrode material as a

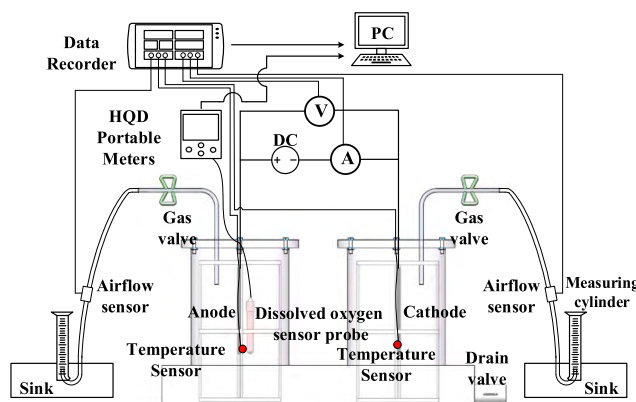


FIGURE 1. Diagram of the experimental platform.

typical example, the present study conducts experimental research on gas production in water and water-saturated coke environment, designs an experimental platform that can collect cathode and anode gases separately, obtains gas evolution characteristics under different operation modes and electrolytes, and summarizes laws of gas generation to provide a reference or guidance for designing the DWGE.

II. EXPERIMENTAL PLATFORM DESIGN OF GAS EVOLUTION CHARACTERISTICS

A. FUNCTION OF THE PLATFORM

A hermetical gas evolution experimental platform is established to collect the anode and cathode gases separately. A stable DC is applied to the electrodes, on which the electrochemical reactions occur. The platform mainly includes a container, a power supply circuit, and a gas collecting part, and the testing parameters and additional detail functions vary with different media. To satisfy the function of collecting the gases separately and prevent the gas mixture from a possible hazard, the container is designed as a U-shaped connecting vessel. The height \times length \times width of the cuboid tank is 0.1 m \times 0.8 m \times 0.4 m. The cylinder is 0.3 m high and 25 cm in diameter. The electrode has a length of 20 cm and a diameter of 1 cm. The concentration of Cl^- in tap water used in this experiment is less than 0.3 mg/L, which is much smaller than that in seawater of 18980 mg/L. Thus, the influence of the chloride ion can be ignored. A diagram of the experimental platform is illustrated in Fig. 1.

B. TESTING PARAMETERS AND METHODS

1) EXPERIMENTAL PLATFORM FOR WATER

The characteristics of oxygen electrolyzed in water are quantitatively analyzed by monitoring the change in dissolved oxygen (DO) near the electrode. The HQD30 portable meter equipped with a sensor probe from the Hach Company is used to monitor the DO. To reduce the interference of the original water's DO, an N_2 bottle is connected to the platform, by which the original DO can be regulated to a fixed value

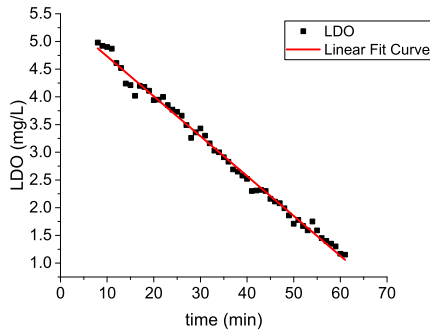


FIGURE 2. DO curve near the anode.

using bubbling with nitrogen, and then remove the N₂ bottle and connect an airbag to the platform.

2) EXPERIMENTAL PLATFORM FOR SATURATED COKE

Considering that the backfilled coke in the DWGE is fully soaked in underground water, saturated coke is formed. Coke and water are completely mixed and filled into the container of the platform and maintained 2–3 cm depths of the water above the saturated coke to observe a gas-evolving phenomenon. At the outlets of the cathode and anode gas paths, water tanks and a measuring cylinder are used for collecting gases, and a gas flow sensor is connected to the path to monitor the gas flow rate.

III. RESULT OF THE GAS EVOLUTION CHARACTERISTICS EXPERIMENT

A. WATER EXPERIMENT

1) ELECTRODE WORKS AS AN ANODE

A DC of 1 A is continuously applied to the electrode for 2.5 h, and a DO curve near the anode is obtained, as depicted in Fig. 2. Carbon steel anode has no oxygen evolved in water, and the DO near the electrode decreases, thereby indicating that oxygen consumption reaction has occurred. The fitting result denotes that the linearity of the DO curve is favorable. The average oxygen consumption rate of the carbon steel electrode is approximately 0.072 mg/(L·min). Given that the DO near the anode has decreased below 1 mg/L after 1 h, minimal changes after such decrease can be neglected, and data within 1 h can indicate the average oxygen consumption rate.

2) ELECTRODE WORKS AS A CATHODE

Cathodic gas is collected, and the gas volume is measured every half hour, as exhibited in Fig. 3. The cathodic gas volume varies linearly with time, and the slope is approximately 311 ml/h (5.2 ml/min). Gas chromatography is utilized to analyze the gas composition, and the results of the analysis demonstrate that the main component is hydrogen.

B. SATURATED COKE EXPERIMENT

The saturated coke in this paper refers to the condition in which all easily drained pores between coke particles are temporarily or permanently filled with water. The gas evolu-

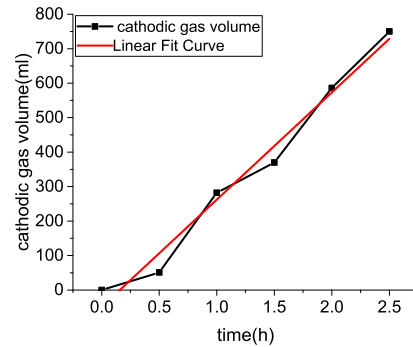


FIGURE 3. Relationship between cathodic gas volume and time.

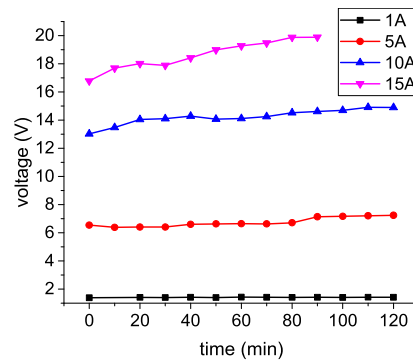


FIGURE 4. Curves of the voltage change with time under 1–15 A.

tion experiment is conducted using saturated coke to simulate the situation in which the feedback coke bed completely infiltrates the underground water. In comparison with water, the phenomenon of electrode gas evolution in saturated coke is not evident. Therefore, a larger current than that in water is used. Five current values (i.e., 1, 5, 10, 15, and 20 A) are impressed.

1) ELECTRODE WORKS AS AN ANODE

When the electrode works as an anode, the gas release in the container is observed. Although the current reaches 20 A, no air bubble is detected on the surface of the coke on the anode-side cylinder.

2) ELECTRODE WORKS AS A CATHODE

When the cathodic electrode is continuously applied with currents of 1, 5, and 10 A for 2 h, no obvious bubble is observed in the water layer above the coke of the cathodic side; furthermore, no gas is collected in the airbag, and the circuit resistance does not change significantly. The curves of the voltage change with time under 1–10 A impressed current, as displayed in Fig. 4, is basically flat. In comparison with the result presented in Section III A, at the same operating current of 2.5 Ah, nearly no gas is produced in water-saturated coke, whereas 780 ml of gas evolves in water.

When the cathodic electrode is continuously applied at a current of 15 A for 1.5 h, small bubbles are clearly observed in the water layer from the top of the electrode. A large bubble



FIGURE 5. Phenomenon of water displacement through gas evolution under 20 A after 1.5 h DC in saturated coke.

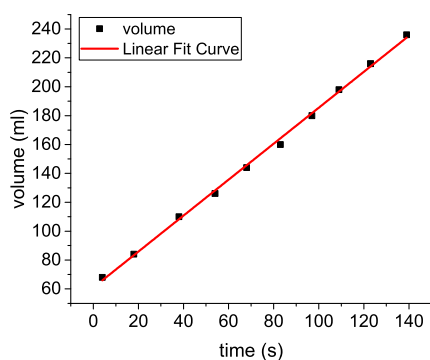


FIGURE 6. Relationship between the water displacement volume and time under 20 A at 1.5 h DC in saturated coke.

will effervesce from the inside of the coke per 20 s on average and change the contact state between the electrode and the coke. The circuit resistance is increased, thus causing the voltage of the 15 A curve illustrated in Fig. 4 to gradually increase with the operating time.

When the operating current reaches 20 A, the cathodic phenomenon is similar to the 15 A operating current situation in the first 1.5 h. After then, the cathode began to violently exhaust gas and the water surface is rapidly bubbling, the gas can be collected by water displacement, as depicted in Fig. 5. The volume is read from the cylinder, and the relationship between the water displacement volume and time is plotted in Fig. 6. The fitting result indicates that the average velocity is approximately 1.24 ml/s.

The loop resistance and cathodic gas flow rate are exhibited in Fig. 7. The gas flow rate is nearly 0 within 0–1.5 h and then rapidly increases and fluctuates at 1.5 h. The fluctuation is related to the intermittent gas release. Simultaneously, the resistance is increased from approximately 1 Ω to 50–60 Ω. Thus, it can be inferred that the critical time point of the gas block effect of the coke in this experiment is approximately 1.5 h. After the gas release path is formed inside the coke, the gas changes the contact state between the coke and the electrode, thereby causing a sudden increase in the loop resistance.

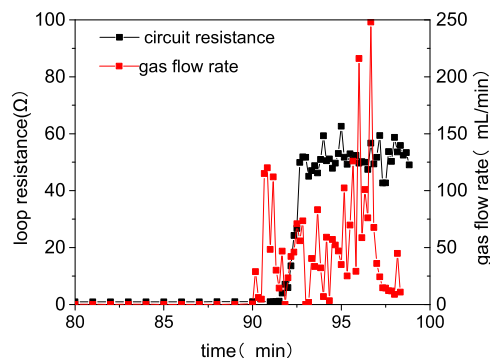


FIGURE 7. Circuit resistance and cathodic gas flow rate under 20 A DC in saturated coke.

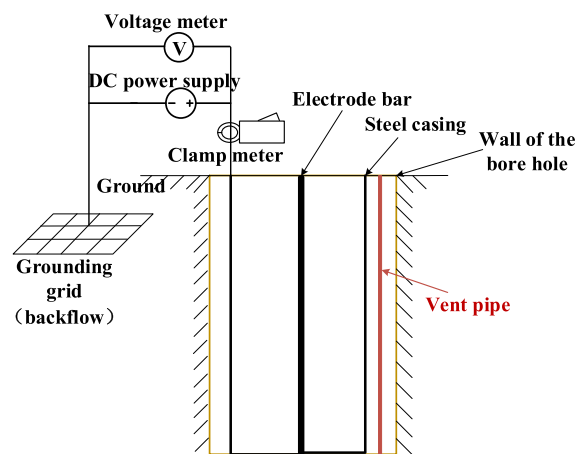


FIGURE 8. Structure and wiring diagram of the 30 m test DWGE.

IV. GAS EVOLUTION EXPERIMENT OF 30 M TEST

To simulate the operating condition of the DWGE, an experiment of a 30 m test vertical electrode is conducted in accordance with the dimension and operating parameters of the actual DWGE. The buried depth of the actual DWGE is 400 m, and the total length from top to bottom is 1000 m. The radius of the steel casing is approximately 0.17 m. When the rated current is 3125 A, the average current density of the DWGE is 3.66 A/m². The test electrode is applied with 100 A DC, and the average current density is 3.12 A/m², which can be equivalent to simulating the gas evolution characteristics of the actual DWGE. The test electrode is positioned in the grounding laboratory of the State Grid Corporation UHV AC test base in Wuhan, China. The structure and wiring diagram are presented in Fig. 8. The mobile DC power supply of the UHV test base, which includes ZBF-100 A/500 V isolation transformer, power supply, and a voltage regulator, is used. The current flows back to the ground grid of the test base. The test electrode includes φ73 mm diameter and 30 m length of carbon steel bar, φ340 mm diameter and 30 m length of steel casing, and φ32 mm diameter vent pipe. The diameter of the borehole is 0.4 m. The coke used in the experiment is spherical particle and its size distribution is: 46% of 75-150 μm, 30% of 150-180 μm, 13% of less than 75 μm, and 11% of 180-250 μm. Before coke is backfilled in the well, the underground water is filled outside the steel casing

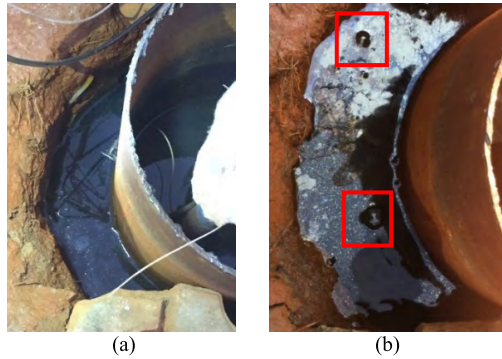


FIGURE 9. Gas evolution of a 30 m test electrode. (a) Anodic operation. (b) Cathodic operation.

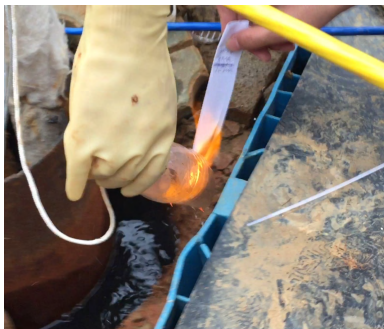


FIGURE 10. Burning gas collected near the bubbles.

and between the steel casing and the bar. The gas evolution characteristics have been comprehensively judged by bubble observation, gas burning, and water sample detection.

The test electrode has continuously applied a current of 100 A for 9 h and works as anode and cathode respectively, observes the gas production at the wellhead, measures the circuit voltage, and calculates the resistance.

A. EXPERIMENTAL RESULT BEFORE COKE BACKFILLING

(1) The circuit resistance is nearly constant over time, and the average resistance is approximately 1.4 Ω before coke backfilling.

(2) When the electrode works as an anode, no bubble is released between steel bar and casing, so does outside the steel casing, as illustrated in Fig. 9(a).

(3) When the electrode works as a cathode, after operating for 10 min, the water outside the steel casing releases bubbles until the ending of the experiment, as depicted in Fig. 9(b). Bubbles are collected from the water into a gas bottle, and then a burning piece of paper stripe is placed. A sound of explosion ('pops') can be heard and is accompanied by a bright flame, as demonstrated in Fig. 10, which can infer that the evolved gas is hydrogen. To determine whether the anode produces oxygen at 100 A DC, the surface water samples outside the steel casing are sent for inspection after operating for 7 and 9 h. The concentration of ferrous and total iron, including Fe²⁺, Fe³⁺, and iron hydrate, are determined, and the proportion of ferrous iron to total iron is calculated, as summarized in Table 1.

TABLE 1. Results of the ferrous iron concentration determination.

Operating time (h)	Fe ²⁺ (mg/L)	Total iron (mg/L)	Fe ²⁺ ratio (%)
7	7.5	18.325	40.93%
9	8	17.432	45.89%

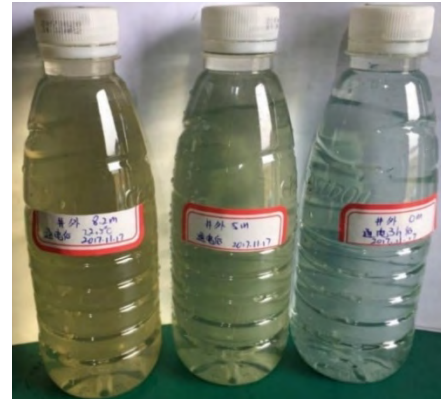


FIGURE 11. Water samples (From the right to the left side are 0, 5, and 8 m samples).

According to the concentration determination results, the ratio of Fe²⁺ to total iron increases with the operating time. This phenomenon may be caused by two reasons: First, the rate at which the electrode metal continuously dissolves Fe²⁺ is higher than the rate at which Fe²⁺ is oxidized to Fe³⁺. Second, the oxygen evolution reaction does not occur; otherwise, Fe²⁺ will be further oxidized to Fe³⁺, and the Fe²⁺ ratio must decrease. Fig. 11 exhibits the water sample obtained from 0, 5 and 8 m underwater outside the steel casing after operating for 9 h. Given that the Fe²⁺ solution is light green, and the Fe³⁺ solution is reddish brown. Thus, according to the color of the water sample, the water is nearly free of Fe³⁺.

Based on the abovementioned experimental results and analysis, when the carbon steel electrode works as an anode, only the oxidation reaction of Fe dissolution occurs and do not produce oxygen. In addition, the continuous gas generation under the cathodic operation is consistent with the phenomenon described in the gas evolution characteristics experimental platform under the condition of the water medium in Section III.

B. EXPERIMENTAL RESULT AFTER COKE BACKFILLING

After backfilling coke into the borehole, a water layer of approximately 0.5 m to 1 m is maintained above the coke.

(1) The circuit resistance at approximately 1.23 Ω is slightly lower than that before coke backfilling, and the resistance value does not change much with time.

(2) No continuous gas production is observed under the anodic operation mode, whereas small bubbles accumulate on the surface within 10 min under the cathodic mode. With the increase in the operation time, the bubbles continuously escape from the water surface after 1 h.

(3) Before backfilling coke into the borehole, the gas generated by the electrolysis moves up to the water surface through the groundwater, and the vent pipe has no obvious influence

on the experimental results; However, after backfilling coke, intermittent drainage phenomenon appears in the vent pipe. The water is sprayed out due to the high gas pressure, which is formed by the gas accumulation in the coke. By burning gas at the end of the pipe, the same flame phenomenon as before can be observed, and the popping sound is heard, indicating that the gas evolved near the bottom of the electrode can be released through the vent pipe. If the pipe is not installed, the gas in the coke will face more difficult exhaust problem, and as the operating time increases, the gas accumulates in the well, and leading to the increase of the grounding resistance. Since the operating time in the test is shorter than practical project, not obviously increasing in grounding resistance is observed during the test.

V. ANALYSIS OF FACTORS AFFECTING GAS EVOLUTION

A. INFLUENCE OF ELECTRIC PARAMETERS

1) INFLUENCE OF IMPRESSED CURRENT AND SURFACE CURRENT DENSITY ON GAS EVOLUTION

Given that the sizes of the electrode in an experimental platform and a 30 m test well are different, the current parameters must be normalized to analyze the influence of electric parameters on the gas evolution. The surface current density of the electrodes in the experimental platform and the 30 m test well are calculated. According to the geometrical parameter displayed in Figs. 1 and 9, the material and resistivity are the input, and a simulation model is established in software to calculate the surface current density.

According to the result of gas evolution characteristics experiment based on the designed platform in Section III, when in water, H_2 can be evolved under only 1 A current (the calculation result of the maximum current density of the electrode is 875.2 A/m^2), whereas more than 10 A current are required to evolve H_2 in water-saturated coke (the maximum current density is 8752 A/m^2). In comparison with the result presented in Section III A, at the same operating current of 2.5 Ah, nearly no gas is produced in water-saturated coke, whereas 780 ml of gas has evolved in water.

According to the result of 30 m test well experiment in Section IV, for the electrode works in the cathodic mode, the continuous bubble can be observed within 10 min before the coke backfilling under the same operating current of 100 A. By contrast, the same phenomenon may be obtained in 1 h after the coke backfilling. Thus, it can be inferred that under the same current of 100 Ah, the electrode demonstrates a larger amount of gas evolved in the water than in water-saturated coke.

Therefore, under the same experimental conditions, the current density required for gas evolution is larger in water-saturated coke than in water, and the total gas production is smaller under the same ampere-hour of current.

In addition, by comparing the experimental results described in Sections III A and IV B, no obvious bubble or gas releasing is observed under 1–10 A current for 1–2 h in the vicinity of a cathode, although the surface density has reached 8752 A/m^2 . By contrast, when the cathodic electrode

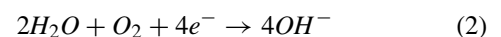
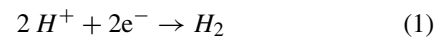
is under 100 A current for 1 h (the calculation result of its surface density is only 24.2 A/m^2), bubbles are released from the water. A high ampere-hour of the impressed current indicates an easy gas evolution; this phenomenon can be explained by Faraday's law, in which the amount of the substance that generates gas through an electrolytic reaction is proportional to the number of ampere-hours.

Notably, considering that the coke particles are conductive, two conductive modes exist in the saturated coke, that is, electron conduction of coke particles and ion conduction of water. According to Faraday's law, a small ampere-hour of work current denotes a minimal amount of gas evolved from the electrolytic reaction, which is the ion conduction mode of water. As the gas amount may be minimal and cannot be observed or collected, it cannot be considered that the electrode does not produce hydrogen at all in saturated coke under low current.

2) INDIRECT EFFECT OF SURFACE CURRENT DENSITY ON THE GAS EVOLUTION PROCESS OF THE ELECTRODE

Given the end effect of the DWGE, the surface current density does not distribute evenly across the length of the grounding electrode, and the current density at the end is higher than the other parts. Considering that the electron migration is faster than the electron gains or loss and its subsequent mass transfer processes in the electrolysis reaction, electrochemical polarization effect occurs when currents flow through electrodes. The electrode potential of the metal deviates from the original equilibrium potential E_e and reaches a new electrode potential value E . The distribution of current density will affect the deviation value, thus indirectly influencing the electrode potential of different parts of the electrode. From the perspective of electrochemical thermodynamics, the reaction trend depends on electrode potential, which essentially establishes the conditions for gas evolution.

According to the experimental results, the following cathodic reactions occur simultaneously on the carbon steel electrode in water.



Anodic reaction



When the entire reaction system reaches a certain equilibrium state, the electrode potential E' is equal to the equilibrium potential E_e of the electrolysis reaction. In accordance with the Nernst equation, the equilibrium potential of each reaction can be calculated.

$$E_e = E^\ominus + \frac{RT}{zF} \sum_j v_j \ln a_j = E^\ominus + \frac{RT}{zF} \ln \left(\prod_j a_j^{v_j} \right), \quad (4)$$

where v_j is the stoichiometric coefficient of the reversible electrochemical reaction, a_j is the activity of the substance, z is the number of gain or loss of electrons, $R = 8.314472 \text{ J/mol} \cdot \text{K}$.

$\text{Pa}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$ is the ideal gas constant, and $F = 96485 \text{ C/mol}$ is the Faraday constant.

The formulas for Reactions (1), (2), and (3) are written in accordance with the Nernst equation (4).

$$E_{H^+/H_2} = E_{H^+/H_2}^\ominus + \frac{RT}{2F} \ln \frac{a_{H^+}^2}{p_{H_2}} \quad (5)$$

$$E_{O_2/OH^-} = E_{O_2/OH^-}^\ominus + \frac{RT}{4F} \ln \frac{p_{O_2} a_{H_2O}^2}{a_{OH^-}^4} \quad (6)$$

$$E_{Fe^{2+}/Fe} = E_{Fe^{2+}/Fe}^\ominus + \frac{RT}{2F} \ln a_{Fe^{2+}} \quad (7)$$

According to the pH calculation formula,

$$pH = -\lg a_{H^+} \quad (8)$$

According to the activity product formula,

$$k_w = a_{H^+} \cdot a_{OH^-} \quad (9)$$

When in the standard state (1 atm, 25°C), H_2 partial pressure is $p_{H_2} = p_{H_2}^\ominus = 1$, and O_2 partial pressure is $p_{O_2} = p_{O_2}^\ominus = 1$; moreover, $k_w = 10^{-4}$. The activity of solid and liquid is 1 (i.e., $a_{H_2O} = 1$). After substituting equations (5)–(7), the equilibrium potentials of Reactions (1)–(3) are calculated.

$$E_{H^+/H_2} = -0.059pH - 0.0295 \lg p_{H_2} \quad (10)$$

$$E_{O_2/H_2O} = 1.23 - 0.059pH + 0.0148 \lg p_{O_2} \quad (11)$$

$$E_{Fe^{2+}/Fe} = -0.440 + 0.0296 \lg a_{Fe^{2+}} \quad (12)$$

Using the concentration of 10^{-6} mol/L of Fe^{2+} as the boundary of iron corrosion, the standard equilibrium line of Fe/Fe^{2+} and the hydrogen and oxygen evolution balance line are derived using Equations (10)–(12), as presented in Fig. 12. When the solution is at the standard state and $pH = 7$, the equilibrium potential is obtained. $E_{H^+/H_2} = -0.413 \text{ V}$, $E_{O_2/H_2O} = 0.817 \text{ V}$, $E_{Fe^{2+}/Fe} = -0.6176 \text{ V}$. When the pH is constant, and the electrode potential is lower than the hydrogen balance line, in accordance with Equation (10), the partial pressure of H_2 must be increased to reach a new equilibrium state, and H_2 is evolved; similarly, in accordance with Equation (11), when the potential is higher than the oxygen balance line, the partial pressure of O_2 must be increased to reach a new balance, and O_2 is evolved. According to the experimental results, Reactions (1)–(3) occur during the operation. Thus, the electrode potential E exceeds the equilibrium line of Fe/Fe^{2+} and below the hydrogen balance line, as illustrated in Fig. 12.

B. EFFECT OF ANODE AND CATHODE OPERATION MODES ON GAS EVOLUTION

The number of moles of gas is calculated using the Faraday equation.

$$n = It/zF \quad (13)$$

Given the standard air pressure and ignoring the molecular volume and interaction between gas molecules, the ideal gas

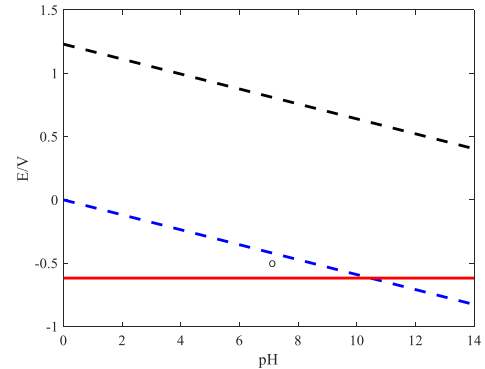


FIGURE 12. Electrode potential-pH diagram of Fe-H₂O.

equation is used to calculate the volume of gas produced within 1 min at 20°C.

$$V = nRT/P, \quad (14)$$

where T is the temperature, K; R is the ideal gas constant, 8.314 J/(mol•K); and P is the standard air pressure, $1.01 \times 10^5 \text{ Pa}$.

Then, the relationship between the ampere-hours and gas volume is

$$V = kIt \quad (15)$$

$$k = RT/zFP \quad (16)$$

In terms of the calculation results, the gas evolution coefficient of O_2 at 20° C is $k_{O_2} = 5.93 \times 10^{-8}$, and $k_{H_2} = 1.19 \times 10^{-7}$. Substituting the ampere-hours of working current, the rate of gas generation when the working current is used for the oxygen-consuming reaction or hydrogen evolution can be calculated.

Given that only Reaction (3) occurs on the anode, no gas is evolved in water or coke. On the cathode, Reactions (1) and (2) occur simultaneously. Thus, the DO in the water decreases, and H_2 is evolved. For the gas evolution experimental platform with a volume of approximately 57.4 L, when the working current is 1 A, and the cathode only reacts with Reaction (1), the hydrogen evolution rate is calculated as 7.5 ml/min, whereas the practical measured gas evolution rate is 5.2 ml/min, which is smaller than the calculation result; if only Reaction (2) occurs on the cathode, the oxygen consumption rate is calculated as 0.086 mg/(L·min), and the measured rate is 0.072 mg/(L·min), which is also smaller than the calculation result. These results are mainly due to the simultaneous occurrence of Reactions (1) and (2), currents are used for both oxygen consumption and hydrogen evolution.

C. EFFECT OF MEDIUM ON GAS PRODUCTION CHARACTERISTICS

The carbon steel electrode in an anodic operation mode does not produce gas in water and coke media. Thus, the difference in gas production characteristics of the two media during cathode operation is mainly discussed in this section.

According to Faraday's law, the gas production is proportional to the ampere-hours of working current. When the

current is small, the contact resistance between the coke and the electrode is not significantly affected by the weakly evolved gas, and the loop resistance is basically unchanged. When the current applied is gradually increased, part of the current that conducts through the ion from the water of saturated coke and the hydrogen evolution also increases. If the gas amount reaches a certain pressure, then the gas release passage will be formed, and the gas bubbles intermittently release upward from the inside of the coke. Furthermore, the contact between the electrode and the coke particles is damaged, and the loop resistance increases with the bubble resistance, thus resulting in the gas block effect.

However, if the working environment of the electrode is water, then all the current conducts through the ion mode, and the gas will be rapidly released, even in low current, because the density of hydrogen is less than air and will not be blocked by coke particles. Therefore, hydrogen is more easily collected from the water than from the coke. Thus, H_2 can be observed and collected at the beginning of the operation.

VI. CONCLUSION

Experimental studies on gas evolution in water and saturated coke based on the platform and 30 m test well are conducted in this paper. A U-shaped connector gas evolution experimental platform, which can collect cathode and anode gases separately, was designed. The carbon steel electrode was used as an example to study its gas evolution characteristics. The experiment can reflect the actual gas evolution characteristics of the DWGE, and the following conclusions were drawn from this study:

- (1) Under 1 A DC, the gas evolved on the cathodic electrode in water is mainly composed of H_2 , and the velocity of evolution is 5.2 ml/min. Gas did not evolve on the anodic electrode, while the average oxygen consumption rate of the carbon steel electrode is approximately 0.072 mg/(L·min).
- (2) When the electrode works in the water-saturated coke under 1 A current, gas has not evolved on either anode or cathode, but the cathode has produced gas evidently when the current is increased to 20 A, and the electrode continuously operates for 1.5 h, causing a sudden increase in the loop resistance and fluctuation of the gas flow rate. However, the anode still fails to produce gas.
- (3) The electrode of 30 m test well that works in the cathodic mode of 100 A in water has exhibited an evident gas-evolving phenomenon, whereas no gas production and only the reaction of dissolution of iron occurs in the anodic mode. When the operating environment is water-saturated coke, continuous gas production cannot be observed until 1 h of cathodic mode operation. In addition, gas is still not produced during the anodic mode, thereby further confirming the above-mentioned experimental results. Moreover, the design of the vent pipe plays a role in practical use.

- (4) According to the comprehensive analysis of the experimental results, a high ampere-hour of the working current allows for an easy observation of the gas production phenomenon, and the current density can indirectly affect the electrochemical reaction. When in water, the electrode potential E exceeds the equilibrium line of Fe/Fe^{2+} and below the hydrogen equilibrium line during the operation. Under the same experimental platform, in comparison with water, the current density required for gas evolution in water-saturated coke is larger, and the total gas production is smaller under the same ampere-hour of current. In addition, the gas production changes the contact resistance between the electrode and the coke, thereby leading to the gas block after a certain critical time.

In the future study, the gas evolution characteristics experiment will be further conducted at the UHV AC test base, and the effects of coke particle size, coke compactness, and contact status between coke and grounding electrode on gas production characteristics will be explored.

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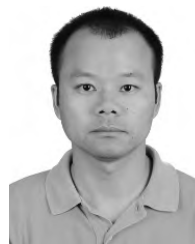
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