Influence Factors of the Generation and Accumulation of Electric Charge on the Oil-Delivery Metal Pipelines

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Abstract The interfacial electrification properties play an important role in the electrochemical corrosion reaction which leads the electrostatic charge to generate and accumulate on the metal surface when the insulating oil flows through a metal pipe. In this paper, the interfacial electrification properties resulted by the oil flow rate and the action of electric charge trapper are investigated by measuring the current and potential on the surface of the test metal pipe. The measured results showed that the current and potential between the metal pipe and the earth increased with the rise of flow rate; and as the flow rate increased, the growth trends of the current and potential difference between two close flow rates increased and decreased, respectively, while there was an electric charge trapper set in the radial direction of the pipe, the measured current and potential decreased compared with that of without electric charge trapper, which was because it captured and caught part of charge in the oil flow bulk to neutralize the opposite charge on the surface of the metal pipe.

KEY WORDS: Flow electrification; Insulating oil; Electric double layer; Metal pipe; Electric charge trapper

1 Introduction

The insulating oil has been widely used in our daily life, while a potential safety hazard exists in the storage and transportation of it owing to its low conductivity [1, 2]. In the process of the pipeline transportation, there will be a relative friction motion between the high-speed flow oil and the pipe inner surface, which leads to the high generation and accumulation of the electrostatic charge on the metal pipe surface and the potential even being up to several thousand volts; hence, it is easy to produce the explosion hazards by discharge [3–5]. At the same time, the metal pipe has been the main common tool for the

insulating oil transportation, which is facing the serious corrosion problems that the electrochemical corrosion may be considered to be the main one. The formed corrosion cells on the metal pipe surface always possess a certain electrode potential which will be influenced by the above potential produced by the electrostatic charge, and then the corrosion process of the metal pipe will be affected. Therefore, the generation and accumulation of the electrostatic charge should be focused and concerned. Not a few literatures have carried out a large number of researches and summarized a set of antistatic safety measures, which have achieved good results [6–11], but owing to the many factors and complicated mechanisms of the charge generation [12, 13], the report about the influence of the flow rate on it is very little, it is necessary to expand and further study the flow electrification phenomenon.

According to the friction theory, when the oil contacts with the metal pipe, the electrostatic charge will be generated on the interface between them due to the electron migration or the selective adsorption of the ions in the oil bulk onto the inner surface of the metal pipe, so an electric

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double layer will be formed in the liquid–solid interface [14–16]. And it contains the diffusion layer due to the thermal motion and the impact layer due to the adsorption (as shown in Fig. 1). Research shows that the thickness of the impact layer is equal to the magnitude of a molecular diameter, while the diffusion layer is usually tens to hundreds of times of it. The diffusion layer thickness can be expressed by Debye length δ [17, 18].

$$\delta = (\varepsilon D / \gamma)^{1/2}, \quad (1)$$

where δ is the Debye length (m); ε is the dielectric constant of the liquid (F/m); D is the diffusion coefficient; and γ is the electrical conductivity (S/m).

But when the oil flows through the pipe, the charge in the impact layer is close to the wall of the metal pipe, which is not affected by the movement of oil flow. The charge in the diffusion layer, however, will be separated from the electric double layer and move along with the oil flow. The charge on the pipe's side is free from the bondage of the Coulomb force due to the departure of the opposite charge in the oil bulk, and it will accumulate on the external surface of pipe because of its high conductivity. If the pipe is grounded, the potential formed by the electrostatic charge on the metal pipe will be changed and lead to the formation of the leakage current, which will

Fig. 1 Schematic diagram of the electric double layer

have an impact on the electrochemical corrosion of the metal pipe [19–21].

In order to restrict the electrochemical corrosion, it is necessary to study the influence of the interfacial electrification properties on the suppression and dissipation of the electrostatic charge on the surface of the metal pipe. In this paper, the generated current and potential on the pipe surface were detected and analyzed, the factors and mechanism of the electrostatic charge accumulation were studied to try to propose a method of controlling the accumulation of the electrostatic charge on the metal pipe surface.

2 Experiment

2.1 Experimental Installation

All experimental measurements reported here were carried out on the system as shown in Fig. 2. Among the experimental apparatus, the circulation pump was used to keep the continuous cycle of the oil in the system, the flow meter used to adjust the flow rate of oil, and the dissipation tank used to leak the electric charge in the oil and keep it without electric charge before entering the test pipe. The test pipe was surrounded by a test wrapper (only used for potential measurement) for inducing the equal potential from the electrostatic field formed by the accumulation of the electrostatic charge on the test pipe and blocking out the external influence when measuring the potentials. The Keithley Model 2450 SourceMeter[®] (this measuring instrument has an enhanced sensitivity with 20 mV and 10 nA ranges and a high input impedance of more than 10 G Ω , and whose resolution is 6.5 and basic measurement accuracy is 0.012%) was used to measure the induced potential generated on the test wrapper, and the leakage current by connecting the test pipe and the earth directly, and the insulating flanges were used to isolate the test pipe with other pipes.

A device called as “electric charge trapper” made of the metallic iron with excellent electrical conductivity as shown in Fig. 3 was placed inside the test pipe and perpendicular to the axis of the pipe, which could have a maximum contact area with the oil flow, but its area was much smaller than that of the pipe.

It is connected with the test pipe for catching the electric charge in the oil and then carrying it to neutralize the opposite charge on the test pipe wall, it means that the separated positive and negative charge are meet again in the “electric charge trapper” and then neutralized. That is to say, under certain conditions, it may achieve the purpose of reducing the accumulation of the electrostatic charge on the surface of the test pipe.

Fig. 2 Experimental installation for potential measurement **a**; for current measurement **b**

Fig. 3 Electric charge trapper

2.2 Experimental Process

The flow of oil in the system was driven by the circulation pump, and the flow rates of oil passing through the test pipe were controlled at 0, 20, 40, 60 and 80 L/min by the flow meter, respectively, which were shown in Table 1. The potential and the leakage current from the test pipe to the earth were measured twice in every flow rate by the Keithley Model 2450 SourceMeter® after the flow state was tending toward stability.

3 Results and Discussion

Figure 4 shows the results of current measurement on the surface of the metal pipe in the different flow rates of the insulating oil.

As shown in Fig. 4, when the test pipe connected to the earth, the leakage currents could be detected at the different

Fig. 4 Results of current measurement in different flow rates of the insulating oil

flow rates. Each of the 3000 sampling numbers belongs to one flow rate, and the flow rate was changed after sampling by the flow meter. When the oil stayed in the metal pipe with static state, the measured current was equal to zero, while in the flowing states, the currents were all greater than zero, and the current always fluctuated around a value; with the increase in the flow rate, there were different grow

Table 1 Flow parameters of the insulating oil in the metal pipe

Flow rate (L/min)	0	20	40	60	80
Reynolds number	0	1062	2123	3182	4246

trends at different flow rates. Because when the insulating oil flowed through the metal pipe, the different flow rates resulted in the various interfacial properties of the metal pipe close to the oil.

When the oil contacts with the pipe surface, the electric double layer will be formed in the liquid–solid interface [as shown in Fig. 5(a)], while the oil flow will make the electric double layer separated and reach a dynamic equilibrium [22].

The charge in the impact layer is close to the inner wall of the metal pipe, which is not affected by the movement of oil flow. The charge in the diffusion layer, however, moves along with the oil flow and forms a streaming current. The separated charge on the pipe's side is difficult to obtain neutralization and will accumulate on the external surface of pipe. When the pipe is grounded, the charge on the pipe surface will flow to the earth and the leakage current will be formed [as shown in Fig. 5(b)].

Figure 6 shows the changes of current on the surface of the metal oil pipeline with the flow rate. From Fig. 6, it was obvious that the measured leakage current increased with the increase in the flow rate, and the growth trend of the current difference between two close flow rates also increased ($\Delta I_1 < \Delta I_2 < \Delta I_3$).

At the very beginning of the flowing, the generated electric double layer was separated by the flow shear force when the oil flowed through the test pipe, and the electrostatic charge was started to produce. With the increasing flow rate, the flow shear force increased which resulted by the rise of the velocity gradient formed at the boundary layer and led to the increase in the degree of separation, and then the more charge were produced and accumulated on the external surface of the pipe, namely the wall leakage current would also increase as the flow rate raised when the pipe wall was grounded.

Fig. 6 Changes in current with the flow rate of the insulating oil

In addition, when the flow rate changed from 20, 40, 60 and 80 L/min, the current varied from 2.5, 4.9, 12.1 and 25.0 pA, and the differences between two of them were 2.4, 7.2 and 12.9 pA, respectively. It meant that in the same difference of flow rate, the difference of the current growth ($\Delta I_1 < \Delta I_2 < \Delta I_3$) increased with the rising flow rate. Based on the flow boundary layer theory (as shown in Fig. 7), the thickness of the boundary layer δ_1 decreases with the rise of the Reynolds number [23]. The magnitude of the boundary layer thickness in the pipe is about 10^{-3} m, which is much larger than the Debye length δ stated above. In other words, the generation of the electric double layer is definitely happening in the flow boundary layer. But as the flow rate increased, the decreasing thickness of the boundary layer resulted in the rise of the flow shear force and the fluctuation motion range. The radial flow part of the fluctuation motion could make more separated charge diffuse into the fluid bulk; these charges had no time to

Fig. 5 Flow electrification with grounded conductive metal pipe

Fig. 7 Schematic diagram of the flow boundary layer

neutralize the wall charge and were taken away by the oil bulk. Therefore, much more separated opposite charges were remained on the surface of pipe under the combined actions of flow shear force and fluctuation motion, which formed the increasing leakage current.

Figure 8 shows the changes in electric potential on the surface of test metal pipe with the flow rate of the insulating oil with or without electric charge trapper. As shown in Fig. 8, it was obvious that the potential of the test metal pipe increased (absolute value) with the increasing flow rate due to the accumulation of the electrostatic charge. According to the theory of electric double layer, when the insulating oil circulated in the test pipe at a certain flow rate, an amount of charge were remained on the surface of pipe while the equal amount of opposite charge were flowed away with the moving oil under the condition of flow equilibrium. In the general case, the negative charge was adsorbed on the solid metal surface, so the positive charge

of electric double layer was in the oil bulk. Therefore, the electrostatic field formed by the negative charge would act around the metal pipe; this behavior would show a negative electric potential on the earth if putting the earth as the zero potential reference point. In other words, with the separation of electric double layer, the generation of the negative charge on the pipe wall increased as the flow rate raised, and the characteristics of negative potential on metal surface were more obvious.

But the potential difference of the test metal pipe between two close flow rates in Fig. 8 was decreasing ($\Delta V_1 < \Delta V_2 < \Delta V_3$), namely the growth trend of potential was gradually decreased with the increase in flow rates. Compared with the growth trend of current difference ($\Delta I_1 < \Delta I_2 < \Delta I_3$) in Fig. 6, there was a certain relationship between current and potential of the pipe along with the flow rate of the insulating oil. According to the Eq. (1), the thickness (δ) of diffusion layer increased with the increase in the diffusion coefficient (D), while D increased with the rising flow rate according to the molecular motion theory, so δ would increase as the flow rate raised. Therefore, the range of the charge distribution in the oil bulk became larger, and at the same condition, the potential difference of unit distance from the pipe wall to the oil bulk became less. But the increase of D resulted in more separated charge diffusing into the fluid bulk, and then the equal amount of opposite charge on the pipe side formed the leakage current when it was grounded.

Figure 9 shows the changes in current on the surface of metal oil pipe with or without charge trapper. As shown in Figs. 8 and 9, the absolute values of current and potential with electric charge trapper were less than that of without electric charge trapper, respectively. It was clear that the electric charge trapper played an important role in the accumulation of the static electric charge. The electric charge trapper made of highly conductive metal materials

Fig. 8 Changes in potential with the flow rate of the insulating oil

Fig. 9 Changes in current with or without charge trapper

was mounted in the radial direction of the metal pipe, which could have a maximum contact area with the oil flow, to capture the charge in the oil flow and then conduct them to neutralize the opposite charge on the pipe wall owing to the electrostatic attraction force and the conduction effect. To a certain degree, this method would reduce the accumulation of the electrostatic charge on the surface of the pipe. As any substance has a certain resistivity and even it is small, there is a certain charge relaxation time correspondingly [24]. Therefore, at this flow rate, not all the charges were conducted to be neutralized, the rest charges which were not neutralized would keep moving in the oil flow, while the charge remained on the pipe wall would form the electrostatic field accordingly with the potential difference smaller than before, and form the leakage current which was also smaller than before. Hence, the absolute values of current and potential were lower than the ones without electric charge trapper.

4 Conclusions

The theory of electric double layer had been widely recognized and used in the electrostatic field, and it also had been being perfected constantly. Based on this theory, in the process of the generation and accumulation of the electrostatic charge on the metal pipe surface, the effect of the flow rates and the action of the electric charge trapper were discussed in this paper. The obtained conclusions were as follows:

- (1) When the test pipe connected to the earth, the leakage current in every flow rate could be detected.
- (2) The absolute values of the measured leakage current and potential all increased with increasing the flow rate of insulating oil in the metal pipe, while the growth trends of the current and potential difference between two close flow rates increased and decreased, respectively.
- (3) The current and potential generated in the case of installing the electric charge trapper were smaller

than that of without the trapper. This was because some electric charge in the oil bulk were caught by the trapper and then conducted to be neutralized with the opposite charge of equal amount on the metal pipe surface.

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