Numerical simulation of oil charge density measured in pipeline by built-in capacitive coupling electrode

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Abstract. This paper presents a method of measuring charge density of oil in pipeline by built-in capacitive coupling inductive electrode. This new type of electrode solved the problem of charge leak in the contacting measurements, and effectively reduced the influence of external factors on the measured results. The three-dimensional model of the electrode in the pipeline was built and was calculated to give the amount of charge captured by the outer electrode which changed with the charge density of oil in the pipeline. The potential of the inner electrode was obtained on the basis of the relationship between the amount of charge and the capacitance, by which the charge density of oil in the pipeline was reflected. This research provided a more effective method for measuring charge density of oil in pipeline.

1. Introduction
Since the 1950s, it has never stopped that the electrostatic accidents of oil tanker caused by loading/unloading oil too fast or other reasons. The accidents of fire and explosion in tankers have also occurred occasionally in our country. The oil products are high insulation and easily produce large amount of electrostatic charge in the process of loading/unloading and transportation. The electrostatic charge brings great risk of safety in the transportation of oil products. Therefore, it's particularly important to monitor the electrification situation in oil transportation. There are a variety of ways to measure oil charge density. The contacting measurement and contactless measurement are the most common. Since contacting electrodes leak charge in measurements and the re-measuring needs to be re-charged to steady state, the contacting electrodes are gradually substituted by contactless electrodes. Contactless electrodes mainly depend on the potential signal which is generated by the induced charge to reflect the charge density. Generally, the inductive portion of conventional electrodes for measuring oil charge density is placed outside of the pipe. Thus, the measuring results can be easily influenced by external factors. In this paper, the capacitive coupling electrode is placed inside the pipe, effectively reducing the impact of external factors.

2. Theory
Built-in capacitive coupling electrode was consisted of a coaxial cylindrical capacitor, the inside pillar was called the inner electrode, and the outside cylinder was called the outer electrode. While the outer electrode captured the charge in oil, the potential of inner electrode changes with the induced charge. For a certain structure of the capacitive coupling electrode, its capacitance value was determined.

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Therefore, the quantity of charge captured by the electrodes was proportional to the potential differences. Once the reference potential of the outer electrode determined, the potential signal of inner electrode was given by \( V_{\text{inner}} = V_{\text{outer}} - \frac{Q}{C} \). This reflected the relationship between the potential of inner electrode and the amount of charge captured by outer electrode. The built-in capacitive coupling electrode was placed in oil pipe, fixed on the pipe wall. In order to avoid the tip effect, the end of the electrode inserted into the pipe was designed to hemispherical. The other end was the fixing disk welded with the inner electrode. Both sides of the fixing disk use special insulation spacer whose diameter was bigger than that of the disk used to insulate the pipe. Simulating the relationship between the amount of charge captured by outer electrode and the charge density of oil in pipe, the relationship between charge density and the potential of inner electrode can be obtained.

3. Model
The three-dimensional model of the electrode in pipe was built. The outer electrode was a hollow cylinder of inner diameter 6 mm and outer diameter 8 mm. The inner electrode was a pillar of diameter 2 mm. It was filled with 2 mm dielectric medium between the inner electrode and the outer electrode. The diameter of the fixing disk and the spacers are 20 mm and 22 mm, respectively. The inner diameter of the pipe was 80 mm, the thickness of pipe wall was 1.5 mm. A diameter of 10 mm circular hole (the outer diameter of electrode was 8 mm) was on the pipe wall, and the electrode was placed in pipe through the centre of the hole, the endpoint of the electrode at the axis of the pipe. In order to build the model, multi-layer drawing was used to build each part, so various parts of the model structure could be shown or hidden. For observing easily, the sleeve welded vertically in the pipe and the bolt for fixing the electrode was hidden, as shown in Figure 1.

![Figure 1. The model of electrode in pipe.](image)

In calculations, the attachments for fixing the electrode have a little influence on the result of the simulation and the setting of their parameters and boundary conditions are complicated. To optimize the simulation process, all attachments are hidden. The Figure 2 was the diagram of the grid model using the finite element method.

![Figure 2. The grid model of electrode in pipe.](image)
4. Simulation process

4.1. Simulation conditions
When oil products flow through the pipe, electrical double layer (compact layer and diffuse layer) is formed at the pipe wall due to different adsorption capacity of various materials. According to the Debye length, the thickness of diffuse layer is less than 1 mm [1]. The rate of oil flow in pipeline is not uniform, viscous layer, transition layer and diffuse turbulent layer being defined from the pipe wall to its center. Since diffuse layer is thicker than viscous layer [2], charge in diffuse layer is brought to the transition layer or the turbulent layer. The oil carries charge and the charge density fits for the equation (1) [3]:

\[ \vec{U} \cdot \nabla q = D_m \nabla^2 q - \frac{q}{\tau} \]  

(1)

Here, \( q \) is the charge density, \( \vec{U} \) is the speed vector of oil, \( D_m \) is the molecular diffusion coefficient, and \( \tau \) is the relaxation time of the oil. This formula is applicable to laminar and turbulent flow. Under normal circumstances, the oil at the entrance of the pipe is not charged. When the oil charges sufficiently in pipeline to reach steady state, the charge density does not change. So,

\[ q \mid_{x=0} = 0, \quad \partial q / \partial x \mid_{x=L} = 0, \]

Here, \( x \) is the pipe axial coordinate, \( L \) is the length of pipe. The boundary conditions at the pipe wall can be obtained as (2)[4]:

\[ \partial q / \partial r \mid_{r=R} = \frac{k \sigma_0 A_i (U_m)^n}{2 F e D_0^2 \sigma} \exp\left( - \frac{W_\sigma - 2 W_0}{kT} \right) = C \]

(2)

Where \( R \) is the pipe radius, \( k \) is the Boltzmann constant, \( F \) is the Faraday’s constant, \( e \) is the electric charge, \( \sigma_0 \) and \( D_0 \) are coefficients of the expressions, \( W_\sigma \) and \( W_0 \) are activation energies, and \( T \) is the absolute temperature. According to the above boundary conditions, the charge density of oil in the turbulent flow can be expressed as (3)[5]:

\[ q(r) = \frac{C \lambda^2 \sec h \left( \delta / \lambda \right) I_0 \left( r / \lambda_T \right)}{\lambda \tanh \left( \delta / \lambda \right) I_0 \left( R / \lambda_T \right) + \lambda_T I_1 \left( R / \lambda \right)} \]

(3)

Which \( q(r) \) represents the distribution of charge density in turbulent zone; \( \lambda = (D_m \tau)^{1/2} \) is the Debye length, \( \lambda_T = (D_T \tau)^{1/2} \) is the turbulence Debye Length; \( r \) is the distance from the center of the pipe; \( I_0 \) and \( I_1 \) are the Bessel functions; \( \delta \) is the thickness of the viscous sub-layer.

4.2. Parameter settings
Various parameters involved must be defined in the simulation process, all parameters’ units use the international unit. In the expression of boundary conditions, \( R=0.004 \) m, \( k=1.38 \times 10^{-23} \) J K\(^{-1}\), \( F=9.649 \times 10^4 \) C mol\(^{-1}\), \( e=1.6 \times 10^{-19} \) C, \( \sigma_0=2.35 \times 10^9 \) S m\(^{-1}\), \( D_0=1.4 \times 10^{18} \) m\(^2\) s\(^{-1}\), \( W_\sigma=5.37 \times 10^{20} \) J [6]. \( A_i \) and \( n \) mainly amends the influence of oil ageing, the roughness of pipe wall or other factors which are difficult to be quantified, and their values are determined in experiment, here \( A_i=20.0, n = 1 \) [6]. The materials of pipe wall, inner and outer electrode in the model are set to High-strength alloy steel. Dielectric material between the electrodes is the epoxy resin, the dielectric constant of 4, oil for Gasoline and dielectric constant of 1.7. In the expression of the charge density, the viscous sub-layer thickness \( \delta \) changes according to the fluid nature of the oil, but the order of magnitude is less than 0.1 mm, and its value is much less than the pipe radius. It is assumed that the thickness \( \delta \) is equal to Debye length in the simulation.
5. Simulation results and discussion

5.1. Charge density distribution of oil in pipe
Three-dimensional model was imported into the electrostatic calculation module to simulate in the preset steady-state. In order to optimize the simulation process, the midpoint of the axis of pipe is set to the origin of coordinates, the axis of pipe and the x-axis coincided, the axis of electrode and the y-axis coincided. Therefore, the charge density was expressed as (4):

\[
q(y, z) = \frac{C\lambda^2 \sec h \left( \frac{\delta}{\lambda} \right) I_0 \left( \frac{\sqrt{y^2 + z^2}}{\lambda_T} \right)}{\lambda \tanh \left( \frac{\delta}{\lambda} \right) I_0 \left( \frac{R}{\lambda_T} \right) + \lambda_T I_1 \left( \frac{R}{\lambda} \right)}
\] (4)

In this condition, shielding the influence of the electrode on charge density, charge density distribution of oil in pipe was shown in Figure 3.

![Figure 3. Charge density distribution of oil in pipe.](image)

As shown in Figure 3, it could be found that low charge density at the center of pipe and high electrification was close to pipe wall. This indicated that the main reason for the electrification in oil pipe was the charge in diffuse layer taken away by oil flow. The simulation was built on the basis of no impurity contained in oil. However, in fact, the oil inevitably carried impurities so that charge density distribution might be different from the simulation results.

5.2. Potential distribution in pipeline and the calculation of the electrode potential
Potential distribution in the model could be obtained by the electrostatics calculation module. According to this module, the outer electrode was defined for the reference point of potential whose electric potential was 0V, and the potential distribution in the model was shown in Figure 4.

From the Figure 4, it could be seen that after the insertion of electrode, the potential distribution changes, the potential fell down around the electrode, which tended to balance after a distance equal to the diameter of the pipe. Under the drive of potential, the electrons moved to the electrode surface from the oil. The amount of charge captured by the outer electrode in the model could be obtained by global calculation. The calculation result was \(-7.553 \times 10^8\) C. The electrostatic module contained the calculation of capacitance. The model of electrode was simulated separately to get a more accurate capacitance. The calculation result was 11.78 pF. The amount of charge and the capacitance value was known, and the potential of inner electrode was given by \(V_{\text{inner}} = V_{\text{outer}} \frac{Q}{C} = 6.412 \times 10^3\) V.
6. Conclusion
This paper presents the model and simulation of a new type built-in capacitive coupling inductive electrode. As contactless electrode, the charge leak is avoided in measurements. The inductive portion of the electrode is placed inside the pipe, effectively reducing the influence of external factors on the measurement results. According to the law of electrification in oil pipe, the distribution of charge was simulated. In the case of the oil free of impurities, the charge density of oil at the centre of the pipe is lower than that of the pipe wall. Setting the outer electrode as the terminal, the amount of charge captured by outer electrode is calculated by the terminal charge calculation module. The amount of charge captured by the outer electrode changes according to the charge density of oil, the relationship between the potential of inner electrode and outer electrode is determined by the electrode capacitance. Therefore, the potential of inner electrode and charge density are interdependent, and the measurement of charge density in oil can be realized by this dependence.

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