The simulation of electrostatics elimination effect influenced by the cross-section shape of discharge needles

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Abstract. In this paper, the electrostatics elimination effect influenced by the cross-section shape of discharge needles in a tube was studied. Firstly, the electrostatics elimination effect was discussed according to the spatial distribution of the electric field. Secondly, the electric field generated by the needles with cross-section of triangle and quadrangle was simulated by finite element method and then compared with the electric field generated by rounded cross-section needles. The results show that the electric field intensity generated by needles of different cross-section decreases in the following sequence: triangle, quadrangle and rounded shape. The needle with triangle cross-section generated the strongest electric field in the direction of tube axis, and the average value of electric field intensity is 12.6% larger than that of the rounded cross-section. So the needles with triangle cross-section are best to the elimination of electrostatics in pipelines.

1. Introduction
In the process of light oil transmission in the pipe, the flowing oil will generate electrostatics. When the electrostatics accumulates to a certain value, it will cause transport security risk. In order to reduce and prevent electrostatic accidents happened in pipe oil transmission, we use a pipeline electrostatic-eliminator at present.

The traditional pipe electrostatic-eliminator included oil conveying inner tube and a grounded outer tube rounded cross-section discharge needles was fixed on the outertube, and got through the inner tube. When the charged oil flowed into the tube, the capacitance generated by inner and outer tubes raised the potential of oil. So, the high potential difference generated between oil and grounded discharge needles. In needle tip area nearby, under the function of the strong electric field generated by the high potential difference, the charge in oil would be neutralized by the heterocharge inducted out by grounding, so as to achieve the purpose of eliminate electrostatics in oil. However, when rounded cross-section needle cusp was abraded, it caused the weakening of point effects. Comparing to the cusp, the other part of needle have less effect on electrostatics elimination, so the whole electrostatics elimination effect of the eliminator would be diminished.

In order to solve the problem, this paper proposes several discharge needle shapes with different cross-section. The cusp and side blades of this needle form the cutting-edge inductive zones, which greatly increases the existence range of cutting-edge inductive zone. It can not only eliminate the

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electrostatic charge near the needle tip, but also can eliminate the electrostatic charge near the needle side. Thus electrostatics elimination effect can be improved.

For purpose of studying the influence of the electrostatics eliminate effected by different discharge needle of several tip angle sections, using the finite element analysis method, this paper do simulations about electric field intensity, which caused by rounded cross-section, triangle cross-section and quadrangle cross-section with different cusp angle, and determine the optimal discharge needle shape.

2. The eliminate electrostatic principle of needles with several cusps
When the charged oil flows into pipe electrostatic-eliminator, due to electrostatic induction, the strong point effects generate by the new needle with several cusps. So the charges in the oil neutralize quickly with heterocharge inducted from ground, and achieve the purpose of electrostatic elimination.

In the pipe electrostatic-eliminator, electrostatic elimination speed is determined by the modules of space electric field intensity value. From the electric field force formula, combining with Newton's second law, we know in any position of space there is:

\[ F_s = e_s E_s, \]  \( \frac{d\vec{v}}{dt} = \frac{d\vec{a}}{dt} \)

In the formula, \( e \) is charge quantity of single charge in the oil, \( m \) the mass of charge, \( E \) the electric field in space. In the flowing oil, they are constants in steady state. Integrate the formula above, it can be expressed as:

\[ e_s E_s \int_v^s \frac{d\vec{v}}{dt} = \int_v^s \frac{d\vec{a}}{dt} \]

In the formula, \( \vec{v} \) oil flow speed, it equates initial speed of charge. If time is constant, to make sure the charge can finish a distance as quickly as possible, we need a larger \( E \), which means a larger potential gradient. If a larger potential gradient exist in pipe electrostatic eliminator, it can eliminate charge faster and have better effects. Therefore, we can use the electric field strength in the pipe size as important evaluation parameter, which can evaluate the oil electrostatic eliminating effect in a pipeline electrostatic-eliminator.

3. The introduce of model

3.1. Geometric part of Model
For studying the electrostatics elimination effect on needle section, this paper constructs model is shown in figure 1. Considering the interval of discharge needle between each layer is 10-40 cm in eliminate charge tube, for simplicity the simulation space is set as a 400 mm×400 mm rectangle to simulate an axis direction section of tube. The lines that simulate out electric field value are expressed as lines \( r=0 \) and \( r=1/2R \) in the sketch.

![Figure 1. Structure of the model sketch and specific shape of the simulation samples.](image)
In the axis of the text space, one rounded whose radius is 4 mm to express the discharge needle section is constructed. These sections can be replaced with triangle and square that inscribe the roundeds. From this, the other two basic types of simulation model can be construct. Meanwhile, based on two kinds of simulation models, through the method of changing interior angle of every section, several samples of needle section was simulated.

3.2. Boundary condition

The boundary conditions must be defined when solving the equations. Generally, speaking the charge density at the entrance of tube is known, and after charge generate in tube, if the tube is long enough the charge density will be fully developed. So the boundary conditions is \( q\mid_{x=0} = 0, \; \partial q/\partial x\mid_{x=L} = 0 \). \( L \) is the tube length. Boundary conditions in the tube wall involve complex electric mechanisms. We simplify mechanisms as "diffusion", according to the relative paper we have the following boundary conditions [1]:

\[
C = \partial q/\partial r\mid_{r=R} = k\sigma_0A(U_a)^e \frac{W_\sigma - 2W_D}{2FeD_0^pT} \exp\left(\frac{-2W_D}{kT}\right) \tag{3}
\]

In this equation, \( R \) is radius of tube; \( F \) is Faraday constant; \( k \) is Boltzmann constant; \( e \) is electron charge; \( K \) is Kelvin temperature; \( W_\sigma \) and \( W_D \) are activation energy of conductivity and molecular diffusion; \( \sigma_0 \) and \( D_0 \) are coefficients in equations of oil conductivity and molecular diffusion coefficient in the form of activation energy; \( U_a \) is average flow velocity of oil.

According to M. J. Lee and J. K. Nelsons’ theory [2], we make \( \sigma_0 = 2.35 \times 10^{-6} \text{ S} \cdot \text{m}^{-1}, \; W_\sigma = 5.37 \times 10^{-20} \text{ J}, \; W_D = 5.22 \times 10^{-20} \text{ J}, \; D_0 = 1.4 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1} \). Meanwhile, the main purpose of adding \( \lambda t \) and \( n \) is fixing the oil aging, wall roughness and other factors that are difficult to quantify description, their values must be confirmed by experiment. Here, \( \lambda t = 20.0, \; n = 1 \) [3].

3.3. Initial condition

Abedian’s research shows that [4], the change of average charge density that in the direction of pipeline can be approximately considered as exponential change in the pipeline, when the charge density obtain full development in oil, the charge density change have nothing to do with \( x \) direction. So:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left[ r(D_n + D_t) \frac{\partial q}{\partial r} \right] + \frac{q}{\tau} = 0 \tag{4}
\]

Therefore, the charge density having different expressions in different layers, according to other literature, the simultaneous equation is expressed as:

\[
\begin{align*}
q_1(y) &= \frac{C\lambda \sinh(y/\lambda) }{\cosh(y/\lambda)} \cosh\left(\frac{y}{2}\right) - C\lambda \sinh\left(\frac{y}{2}\right) \\
q_2(r) &= \frac{C\lambda^2 \sech(y/\lambda) I_0(R/\lambda_t) }{\lambda \tanh(y/\lambda)} I_1(R/\lambda_t) + \lambda \tanh(y/\lambda) I_1(R/\lambda_t)
\end{align*} \tag{5}
\]

In the simultaneous equation, \( \lambda = \sqrt{D_0 \tau} \) is Debye Length; \( \lambda_t = \sqrt{D_t \tau} \) is turbulence Debye Length; \( r \) is distance to pipe center; \( y \) is distance to pipe wall; \( q_1 \) represent charge density distribution in the sticky bottom layer; \( q_2 \) represent charge density distribution in turbulence core area; \( I_0, I_1 \) is Bessel function; \( \delta \) is the thickness of sticky bottom layer; it is changed by difference of oil fluid property, but the magnitude under 0.1 mm, the value is far less than the radius of the pipeline, here it have a same length as the Debye Length [5]. So when the electric field value in some positions were discussed, only the value of \( q_2 \) was considered.

The materials of the samples are set to high strength steel alloy and the relative dielectric constant
is 1. The rectangular space around the sample is defined as limited size space, and fill it with the charge density that defined by equation. The material inside of the model is set to kerosene and the relative dielectric constant is set to 1.7, which refer to JP4 kerosene. The potential of needle is set to 0 V, and then the electric field and potential distribution in the pipeline section can be calculated.

Above all, in order to avoid the simulated result differences caused by the different parameters above, the test samples in the simulation are all in the same file and use the same kind of grid partition method and the same solver.

4. Result of simulation and discussion

The electric field intensity distribution in the tube was shown in figure 2. Electric field intensity distribution effected by several different needle shapes that with three cusps was extracted.

![Figure 2. The electric field intensity distribution caused by three cusps needle section with 10° cusp angle.](image)

In order to assess the electrostatics elimination effect of different needles with three cusps and four cusps, electric field intensity average in the space and particular directions need to be compared. In this paper, needles whose cross-sections have 10°-90° blade cusp angle were chosen, and then the effect of cross-sections on average field intensity was simulate. Similarly, needle cross-sections was replaced by a circumscribed rounded section, and then the electric field intensity average in corresponding place were simulated, all values above shown in figure 3-5.

In figure 3, x-coordinate represents the tip angle of cross-section, and y-coordinate represents the module value of electric field intensity. From the roughly trend of the curve in graph, it shows that when the tip angle getting smaller, the average value of electric field intensity module in \( r=0 \) position tend to increase. Meanwhile, comparing the maximum with minimum values that express the four cusps needle with 10° angle and three cusps needle in figure above, it turns out that the electric field intensity that formed by three cusps needle section with 10° cusp angle is 12.6% is higher than rounded section needle in this space.

The figure 4 expresses the average value of electric field intensity generated by the needle section with different tip angle in the \( r=R/2 \) position. In the image above, the electric field intensity have a minimum when the tip angle is around 40°, therefore this angle should be avoided for use in practice. Comparing the maximum with minimum values that express the three cusps needle section with 10° cusp angle and quadrangle needle in table above, it turns out that the electric field intensity that formed by three cusps needle section with 10° cusp angle is 0.05% is higher than rounded section needle in this space.
Figure 3. Average value of the electric field module when $r=0$ and with different needle section.

Figure 4. Average value of the electric field module when $r=R/2$ and with different needle section.

Figure 5. Average value of the electric field module with different needle section in the tube section.

The figure 5 expresses the average value of electric field intensity generated by the needle section with different tip angles in space. Similarly, comparing the maximum with the minimum values that express the three cusps needle section with 10° cusp angle in figure above, it turns out that the electric field intensity that formed by three cusps needle with 10° cusp angle is 1.02% is higher than rounded section needle in this space.

Although there may exist errors because of meshing is not much fine in the area nearby tip needle, but the three cusps section needle that have smaller cusp angle can form higher electric field intensity than common rounded section needle.

5. Conclusion

This paper gives a potential distribution diagram affected by different charge needle section on tube axial section, and simulates the electric field model average in tube section and particular direction. From the simulation results, the triangle needles that have smaller section cusp angle can form stronger electric field than common rounded section in tube, especially in the axial direction of tube section, and the electric field model average growth is 12.6%. In the whole space, average of the electric field model also can increase by 1.02%. Considering that charge needles are multilayer ring arranged in the
electrostatics elimination tube, actually there will be more charge needles than that in the model for the static elimination tube. Therefore, in practice the point effects formed by more needles with smaller angle will increase electric field model average more than before, thus it is benefit for charge needle to collect the charge in the oil.

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