Research on incentive electrostatic discharge in tankers during oil filling

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Abstract. This paper introduces the mechanism of oil charge and discharge and discusses its types and formations during oil loading and transporting. Moreover, the influence factors of the oil discharge were clarified. The charge current in the oil storage tanker was preliminarily calculated and three stages of charge accumulations were discussed and calculated in detail. The staged charge accumulations include charge unfreezing, charge free surface, and charge accumulation.

1. Introduction
More disasters caused by the electrostatic discharge often happened when the oil was filling into the tank. As the flammable oil is ignited by the electrostatic discharge, it relates to two basic physical phenomena. One is the brush discharge on the electrophorus oil surface, and the other is the spark discharge of isolated conductor. The isolated conductor could be sampling pot, tube, metal fittings, human body, and small suspend object, even the tank truck or the tank car, etc. If the two types of discharge could be avoided and the accumulated electrostatic energy could be released safely, the oil would be loaded, unloaded and transported safely. So to prevent electrostatic discharge to the oil is very important.

The circumstances of electrostatic discharge and safety velocity in oil storage tanker are very important. According to the charge conditions of electric field intensity in different dangerous parts and the ignition possibility of oil vapor in the tanker, the whole oil transportation process could be divided into beginning stage, filling stage and finished stage.

2. ESD harm and countermeasure in oil pipe

2.1. ESD basic rule of flowing oil in pipe
Commonly, the pipe transporting liquid petroleum products is made of steel and (or) aluminum, but the joint part and soft connecting part may also be made of rubber, plastic or latex, even sometimes conductive plastic. The characteristic of electrostatic discharge (ESD) of the oil pipe, regardless of being made of any material, is mainly determined by the flow velocity of oil, the diameter and length of the pipe, and also depends on the texture of material of pipe, the degree of roughness inner pipe and the resistivity of liquid.

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If the volume charges density of oil flowing in the pipe is \( \rho_m \), the current of fluid flow would be

\[
I = \frac{Q}{t} = \frac{\rho_m \pi D^2 L}{4t} \frac{\pi}{4} D^2 V \rho_m
\]

(1)

Considering the saturation density of charge \( \rho_{m\infty} \) in pipe and the pipe length long enough the charge density could achieve saturation, equation (1) would be

\[
I = \frac{\pi}{4} D^2 V \rho_m \left( 1 - e^{-\frac{L}{\tau}} \right)
\]

(2)

\( V \)-Flow velocity of oil in pipe;
\( D \)- Diameter of oil pipe;
\( \rho_{m\infty} \)-Saturation density of charge of fluid flow;
\( L \)-Length of oil pipe;
\( L_0 \)-Saturation length of oil pipe;
\( t \)-Time.

It comes to the conclusion that, while liquid petroleum products flowing in the pipe, the current of fluid flow is proportional to flow velocity and the diameter of the square of pipe, at the same time, also to the length of pipe if it is saturation length of oil pipe. But the current would reach a stable value when the pipe is saturation length. But the above equation is still different with the actual situation. A more reliable empirical formula is achieved as following:

\[
I_{\infty} = AD \alpha V^\beta
\]

(3)

\( A \)- Constant of proportionality;
\( \alpha \)- Determined by the relationship between the average current and diameter of pipe;
\( \beta \)- Determined by the relationship between average current and flow velocity in pipe.

Data show that it is proportional when \( A = 0.58 \times 10^{-6} \sim 3.75 \times 10^{-6} \), \( \alpha = 0.87 \sim 2 \), \( \beta = 1.6 \sim 2.4 \) and the flow velocity and the diameter of pipe are the main factors to cause ESD in oil pipe.

2.2. Affection of pipe length to ESD

It is commonly considered that the longer the pipe is, the stronger the charge is. Actually, the charge conduction could still exist no matter how much the electrical conductivity of liquid would be. So the longer the pipe is, the greater the conduction effects of charge is, and the more quickly the increase of charge leak and neutralization is. But it is not a linear increase in enlargement of the fluid current, which was caused by oil flowing, with the increase of pipe length. General test has proved that it would be an exponential relationship and reach saturation. In different kinds of pipe length, the fluid current comply with the following rule

\[
I_L = I_{\infty} \left( 1 - e^{-\frac{L}{\tau}} \right)
\]

(4)

\( V \)-Flow velocity of oil in pipe;
\( t_{\infty} \)-Saturation current of fluid flow;
\( L \)-Length of oil pipe;
\( \tau \)-Time constant of fluid flow ( \( \tau = \epsilon \rho \) ).

If we assume the relative dielectric constant \( \epsilon_r = 2 \) (for oil commonly, \( \epsilon_r = 2 \sim 4 \)), we could calculate the lengths of pipe when fluid flow currents reach saturation as various liquid flowing in the pipe. The average charge accumulated in tanker could be calculated as following equation:

\[
Q = I_L \tau \left( 1 - e^{-\frac{1}{\tau}} \right)
\]

(5)
I_s - Saturation current of fluid flow;  
\( t \) - Time of filling oil;  
\( \tau \) - Time constant of fluid flow (\( \tau = \varepsilon \rho \)).

3. ESD harm and countermeasure in oil tanker while filling

3.1. Charge diasporas in oil tanker

In order to simplify the problem, we start with the charge diasporas in metal tanker full filled with charged oil. It was assumed that the whole charge in tanker is \( Q \). Under the effect of inner electric field, the electrostatic charge would distribute on the surface of oil and start to loss out through the wall of tanker. According to the law of charge conservation, the reduce volume charge in tanker should equals to the volume charge lost out through the wall of tanker.

\[
-\frac{dQ}{dt} = \oint j \, ds \quad (6)
\]

- \( \oint j \, ds \) - Integral of a closed surface;  
- \( j \) - Charge lost out through the wall of tanker.

\( j = K E \) by Ohm’s law, \( K \) is the electrical conductivity of fluid flow and \( E \) is the electrical field strength of the wall. And through Gauss theorem, we could get

\[
\oint E \, ds = \frac{Q}{\varepsilon,\varepsilon_0} \quad (7)
\]

\[
-\frac{dQ}{dt} = K \frac{Q}{\varepsilon,\varepsilon_0} \quad (8)
\]

The Initial conditions are that when \( t=0 \), \( Q=Q_0 \), the charge complies with decay law as time goes by.

\[
Q = Q_0 e^{-\frac{\varepsilon,\varepsilon_0}{\varepsilon,\varepsilon_0}} = Q_0 e^{-\frac{\varepsilon,\varepsilon_0}{\varepsilon,\varepsilon_0}} = Q_0 e^{-\frac{t}{\varepsilon,\varepsilon_0}} \quad (9)
\]

If we take a tiny volume \( \Delta V \), in which the first volume charge density is \( \rho_0 \) and at the other time it is \( \rho \), from the charged oil tanker, the electrostatic charge in the volume element at arbitrarily moment is \( \Delta Q = \rho \Delta V \) which would be substituted into (8).

\[
\frac{d\rho}{dt} = -K \frac{\rho_0}{\varepsilon,\varepsilon_0} \quad (10)
\]

\( t = 0, \rho = \rho_0 \), after integrating, above equation would be

\[
\rho = \rho_0 e^{-\frac{t}{\varepsilon,\varepsilon_0}} \quad (11)
\]

It indicates that the volume charge density complies with the exponential decay as time goes by. And the decay is determined by the time constant \( \tau \).

3.2. Charge cumulating in oil tanker

3.2.1. Unfree surface of oil

It is also named as float top type tank filling. When charged oil was filled into tanker the charge would be conducted out the tanker through the wall, and the charge in tanker would reduce with time. The conduction current density is assumed to be \( \dot{j} \), the conduction current through the wall should be
\[ I = \oint_S j ds = \oint K E ds = K \frac{Q}{\varepsilon, \varepsilon_0} = \frac{Q}{\tau} \]  

(12)

### 3.2.2. Free surface of oil

Taking the circle as a closed surface, the following equation could be gotten by Gauss theorem.

\[ Q = \oint_S D ds = \oint_S D_n ds = \int_{w} D_{sw} ds + \int_A D_{sa} ds \]  

(13)

\[ \int_{w} D_{sw} ds \] is the surface integral of the contact part between oil and wall, \( D_{sw} \) is the normal direction component of electric displacement on the interface. \[ \int_A D_{sa} ds \] is the surface integral of the free surface, \( D_{sa} \) is the normal direction component of electric displacement on the free surface. If there is no surface charge on the free surface, we could calculate \( D_{sa} = D_{la} = D_{la} \), \( D_{la} \) is the normal direction component of electric displacement on the interface between air and oil. \( D_{la} \) is the normal direction component of electric displacement on the air interface.

The current conducted through the wall should be

\[ I = \oint_{w} j ds = \oint K E ds = \frac{K}{\varepsilon, \varepsilon_0} \int_{w} D_{sw} ds \]  

(14)

Substituting equation (13) into (14), the result is

\[ Q = \frac{\varepsilon, \varepsilon_0}{K} I + \int_A D_{sa} ds = \tau I + \int_A D_{sa} ds \]  

(15)

So

\[ I = \frac{1}{\tau} \left( Q - \int_A D_{sa} ds \right) \]  

(16)

If the inflow current \( I_i \) is substituted, we would get following equation by conservation of charge.

\[ \frac{dQ}{dt} = I_i - I = I_i - \frac{1}{\tau} \left( Q - \int_A D_{sa} ds \right) \]  

(17)

Assumed that the current diasporas was stable, then

\[ I_i = \frac{1}{\tau} \left( Q - \int_A D_{sa} ds \right) \]

\[ Q = \tau I_i + \int_A D_{sa} ds \]  

(18)

### 3.2.3. Charge accumulation in tanker while surface charge density is \( \sigma \)

Actually, the interface between air and liquid combined with the wall of tanker to form a closed surface. According to Gauss theorem, we would get as following:

\[ Q = \oint_S D ds = \int_{w} D_{sw} ds + \int_A D_{sa} ds = \frac{\varepsilon, \varepsilon_0}{K} \int_{w} E_{sw} ds + \frac{\varepsilon, \varepsilon_0}{K} \int_A E_{sa} ds \]

\[ = \tau \left( \int_{w} j_{sw} ds + \int_A j_{sa} ds \right) \]  

\[ D_{sw} \] is the electric displacement vector on the solid-liquid interface, \( E_{sw} \) is electric field strength, \( j_{sw} \) is the normal component of current density. The current conducted through closed surface should be
\[
\int_{S} j_{w} \, ds + \int_{A} j_{n} \, ds = \frac{Q}{\tau} \tag{20}
\]

Like above calculation, if the inflow current \( I_s \) is substituted, then
\[
\frac{dQ}{dt} = I_s - \left( \int_{S} j_{w} \, ds + \int_{A} j_{n} \, ds \right) = I_s - \frac{Q}{\tau} \tag{21}
\]

When the current is stable,
\[
I_s = \frac{Q}{\tau} \quad Q = I_s \tau \tag{22}
\]

So we get the whole charge in oil except the surface charge in tanker while the situations are stable. If there is surface charge, the result should be the plus of the two parts of charges.
\[
Q_{\text{whole}} = \tau I_s + \sigma ds \tag{23}
\]

This integral includes the whole surface of the liquid. And it is more dangerous if the surface area is bigger because of the increasing of surface charges. In order to reduce the ESD harm in tanker, one method is to reduce the free surface in oil tanker. We could reduce the potential of oil surface by dividing a big tanker into a lot small space using metal material. Another method is to fill with insulating gas into the air space in tanker to reduce the charges of the free surface of liquid.

From above discussing, we know that the electric field strength in air space would be enhanced as the increasing of surface charges. At the same time, the possibility of ESD caused by surface discharge in air space would increase, too. The discharge will happen certainly as the space electric field exceeds the Breakdown electric field.

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