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Numerical study on electrostatic potential distribution of large cylindrical oil tanks

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ABSTRACT

This study carried out a numerical simulation of electrostatic potential distribution in the cylindrical oil tank, focusing on spatial distribution of electrostatic potential and the variation tendency of the potential in the filling operation. Electrostatic potential distribution of stationary oil was illustrated, and the relationship between the electrostatic potential distribution and some parameters of the tank and oil was analyzed as well. Dynamic electrostatic distribution was studied when charged oil is filling into the tank, and ESD prevention measures' effects on electrostatic potential distribution were simulated. Finally, calculation results of two other types of oil tanks were presented in brief.

Introduction

Static charges can be generated when two objects of different materials come into direct contact with each other and then separate [1]. As same as the contact and separation between two solid objects, the oil flowing in pipelines and tanks can also generate static charges due to some relative motions such as flow, filtering, jet, impact and settlement [2,3]. Therefore, a large amount of charges will be accumulated in oil flow [4]. As the static charges are constantly accumulated, there may be the possibility of electrostatic discharge when the electrostatic potential of oil surface reaches a certain value, which will make the tank exposed to a huge hidden danger [5]. According to incomplete statistics, there were 116 accidents occurred in the United States from 1960 to 1973. And the figure in the former West Germany from 1962 to 1973 is 22 [1]. Hence it is of great importance for scientific research of electrostatics distribution in oil tanks.

To effectively control and reduce fire and explosion accidents caused by static electricity in oil tanks, it is necessary to understand the mechanism of the generation and discharge of static electricity. It is quite important to understand the distribution of electrostatic potential in tanks so as to reduce the electrostatic hazards. For a long time, many scholars have studied the electrostatic problems of oil tanks. H. Shi [6] obtained the analytical solution of electrostatic potential of a cylindrical tank using the separation of variables. And the potential of gas space and electric field intensity were also obtained in Ref. [6]. Through some experiments, a Japanese scholar Y. Matsubara et al. [7] found that in the filling process the average charge density of oil decreases with the increase of surface height and when the filling rate reaches 50%, the maximum potential of oil surface will occur. C. Liu et al. [8] came up with a numeric model of over-relaxation iteration of electrostatic potential in a cylindrical tank using the finite method. The distribution laws of electrostatic potential in oil tanks were analyzed and the influence of the structure and operating parameters on electrostatic potential was also addressed in Ref. [8].

Although scholars mentioned above have done lots of research on static electricity in storage tank, studies on the dynamic process of the electrostatic potential during filling operations are limited. J. Wang [9] studied on the dynamic process and showed the impact of charges of free oil surface on interfacial potential. L.G. Britton et al. [10] found the relationship between electrostatic potential and tank size.

However, investigation of the electrostatic distribution law for large oil storage tanks is not enough and further research is still needed. In this paper, numerical simulation of electrostatic potential in a large cylindrical tank is carried out. Dynamic changing process of potential is presented explicitly and effects of some parameters on electrostatic potential are analyzed. The influence of two electrostatic protective measures on the electrostatic potential

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distribution is studied as well, and a comparison between the elimination effects of each measure is made.

Methods

Laplace and Poisson equations

Most oil tanks used in production process are cylindrical, so the model of an oil tank can be constructed as shown in Fig. 1. Fig. 1 shows an oil tank of radius “R” and height “H”. In this model, the assumption is that there has been part of the charged oil of which the depth is “h” and the upper part is gas space. Actually most of oil tanks are in this state. Assuming that in the steady state, the distribution of charge density in oil space is uniform and there is no charge in gas space, the gas space and oil space respectively satisfy the Laplace equation and Poisson equation [6]. The equations are given by:

$$\frac{\partial^2 U_1}{\partial r^2}+\frac{1}{r}\frac{\partial U_1}{\partial r}+\frac{\partial^2 U_1}{\partial z^2}=0 \tag{1}$$

$$\frac{\partial^2 U_2}{\partial r^2}+\frac{1}{r}\frac{\partial U_2}{\partial r}+\frac{\partial^2 U_2}{\partial z^2}=-\frac{\rho}{\varepsilon} \tag{2}$$

where U_1 (V) is potential of gas space; U_2 (V) is potential of oil space; ρ(C/m^3) is charge density of oil space; ε is relative dielectric permittivity of oil; z (m) is vertical height and r (m) is horizontal distance.

As the metal tank is grounded, potentials of all boundaries of the tank should be 0, and hence the boundary conditions are as follows:

$$U\big|_{r=R}=U\big|_{z=H}=U\big|_{z=0}=0 \tag{3}$$

In addition, if there is no charge on oil surface, on the gas–oil interface the following equations should be satisfied:

$$\varepsilon_0\frac{\partial U_1}{\partial z}=\varepsilon\frac{\partial U_2}{\partial z} \tag{4}$$

$$U_1=U_2 \tag{5}$$

where ε_0 is relative permittivity of gas space.

The mathematical model of charge density

When oil with small conductivity (below 10 pS/m, 1 pS/m $=10^{-12}\Omega^{-1}\text{m}^{-1}$) flows in the pipeline, friction will occur [4]. The static electricity is produced at the same time, and its amount depends on the charging current I (A) [11].

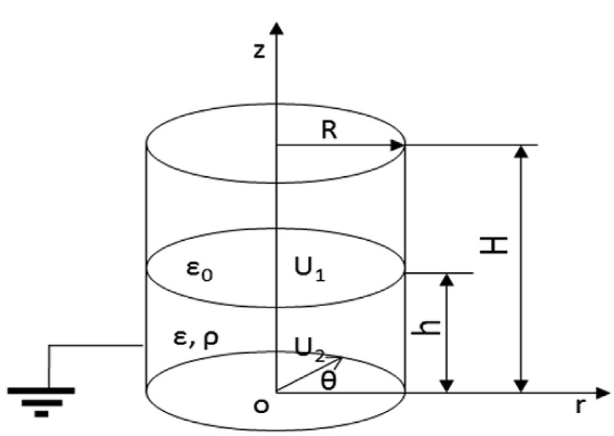

Fig. 1. The model of a vertical cylindrical oil tank.

$$I=K\nu^2d^2 \tag{6}$$

where K is a constant depending on the conductivity of oil; v (m/s) is the average flow rate of oil and d (m) is the diameter of the pipeline.

Assuming that the volume of the original oil in a tank is V_0 (m^3), as the oil is being filling into the tank, the relationship between volume V (m^3) of the oil and time t (s) can be given by:

$$V=V_0+\pi(d/2)^2\nu t \tag{7}$$

According to the study of Y. Matsubara [7], the dynamic mathematical model of charge density ρ (t) can be given by:

$$\rho(t)=\frac{I_{in}\tau}{V}(1-\exp(-t/\tau)) \tag{8}$$

where I_{in} (A) is the current flowing into the tank and τ (s) is relaxation time of oil.

Here I in Eq. (6) is the same as I_{in} in Eq. (8), hence Eq. (6)–(8) can be integrated into one equation:

$$\rho(t)=\frac{K\nu^2d^2\tau}{V_0+\pi(d/2)^2\nu t}(1-\exp(-t/\tau)) \tag{9}$$

Numeric cases

In this paper, numerical studies on a large steel cylindrical storage tank with charged oil are carried out and some technical parameters are shown in Table 1. It is necessary to mention that these parameters are determined according to actual working conditions of a local petrochemical plant. Electrostatic potential distribution of stationary oil and filling process are respectively calculated. When calculating the potential distribution of stationary oil, we mainly focus on the spatial distribution of electrostatic potential, and the relationship between the potential and each parameter of oil. A dynamic changing process of the potential during filling operation is presented as well.

When building the mathematical model, some parts of the tank (such as the staircase and stiffeners) are ignored. That is because they have little influence on the potential distribution of the entire tank.

Results and discussion

Electrostatic potential distribution of stationary oil

In order to find the law of electrostatic distribution in the tank, the stationary and flowing oil are analyzed in the paper

Table 1
The technical parameters of a cylindrical tank.

Parameters	Values
Height of the tank, H (m)	16
Radius of the tank, R (m)	10
Relative permittivity of oil, ε	2
Relative permittivity of vapor space, ε_0	1
Diameter of filler orifice, d (m)	0.2
Flow rate, v (m/s)	6.35
Relaxation time of oil, τ (s)	300
A constant, K	1.0*10^{-5}