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Analysis of Static Electricity Generated in Petroleum Pipeline Transportation Based on the Generalized Gray Incidence Model

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In order to reduce the accidents caused by static electricity, simulative experiments were carried out to obtain the relationship between electrostatic and six factors in petroleum pipeline transportation. The electrostatic current generated in simulative petroleum pipeline was measured. After several groups of experiments, six factors were determined to be of great influence on the electrostatic generation, namely the length of petroleum pipeline, the diameter of pipeline, the roughness of pipeline, the velocity of oil flow, the electrical resistivity and the kinematic viscosity of oil material in the pipeline. The experimental data are analyzed based on the Generalized Gray Incidence Model, and then from its ranking results, the most critical factor and lesser important ones can be distinguished. The experimental data and analysis results show that the velocity of fluid is the most critical factor leading to the generation of static electricity.

1. Introduction

Recently, with the rapid development of the petroleum pipeline industry, a lot of accidents caused by static electricity were occurred (Zhang and Chai, 2010). These electrostatic discharge accidents were likely to result in the petroleum pipeline rupture and leakage, which may even lead to larger fire and explosion accidents. The study of the key factors of electrostatic discharge becomes very essential, and it will also improve the corresponding technical equipment and safety management in petroleum industry (Wang et al., 2016; Zhang et al., 2016). However, those electrostatic accidents in pipeline flow were resulted from a variety of reasons and impact factors, and between which the relationship is extremely complex. It is important to find out the most critical factor to avoid the occurrence of static electricity accidents. At present, many researches often use single assessment model in analysis of the key factors of electrostatic in pipeline flow without consideration of the relevance and complexity among those factors (Alkhazaleh and Duwairi, 2016; Benarab et al., 2016; Cardinale et al., 2016; Yan et al., 2011; Yin and Tian, 2013; Gulyás et al., 2013; Pidoll, 1997). As a result of that the loss prevention in petroleum safety caused by electrostatic develops relatively slowly. The generalized gray relational incidence model is the mathematical model which may obtain the correlation degree between maternal factors and sub factors, and it can be applied to study the relationship between quantity and influence factors for electrostatic generation. This model has the advantages of three linearity requirements:
(1) The original data is not harsh, which means there is no strict regulations on the capacity of samples (Zhou et al., 2007). Since it is serious lack of experimental data in electrostatic generation, such problem with a high gray degree would more likely to be solved;
(2) The calculated results are accurate, as quantitative results of the numerical simulation and qualitative analysis results are matching together (Wei et al., 2012);
(3) Compared to the original gray correlation method, the generalized gray incidence model is more concise, and it is easy to be programmed by many computer languages such as the visual basic software, so it would be simple to get the calculation result from this model. The simulative experiments is establish to measure the electrostatic current in pipeline flow under different conditions. Then the generalized gray incidence model is

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used to the analysis of the experimental results to find out the most critical factor among six factors which is of great influence on electrostatic generation. Finally, the corresponding control methods are proposed based on the theoretical analysis to improve safety management in petroleum pipeline.

2. Experimental system of electrostatic in the flow of petroleum pipe

2.1 Experimental apparatus

Test device mainly consists of oil storage tanks, filter, oil pump, control valves and testing sections. The oil storage tanks are two oil containers. The filter is an electrostatic generator, and the oil pump gives power to the oil flow. The control valves are mainly used to adjust the oil flow rate in the testing sections according to different conditions. Before the test, it is required that the ambient temperature and humidity remain constant, and the storage tank and petroleum pipelines should be delivered with insulation. When opening the oil pump, oil flow starting from the storage tank travels through the filter into the pre-laying oil pipelines. Then it reaches testing sections for which the entire pipeline is used to measure the electrostatic current by the magnetoelectric microampere measurement. In order to ensure the accuracy of the test data, the testing pipelines are divided into two sections of the same configuration of parallel pipeline, and the measurement data are the average of the two testing results. The schematic diagram of the experimental system is shown in Figure. 1.

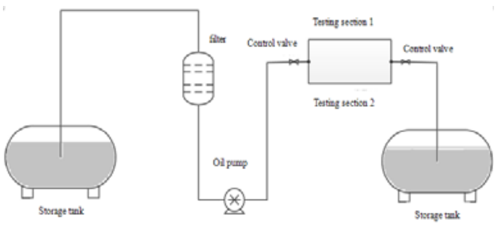

Figure 1: The schematic diagram of experimental system

2.2 Procedures of electrostatic measurement in oil flow

According to the actual working conditions of the oil flow in pipeline, the static electricity generated in the pipeline is mainly determined by the characteristics of the pipeline itself, the physical properties of the oil material and the velocity of oil flow. The characteristics of the pipeline include pipeline length, pipeline diameter, and pipeline roughness, filter size, filter separators and other factors. The physical properties of the oil include oil conductivity, moisture content, viscosity, temperature and so on. Because of the testing equipment and measuring instruments under objective conditions, combined with relevant information (Pu and Wang, 2006; Guo, 2011), during the electrostatic generation process, the parent factor X_0 of the electrostatic generation is most relevant to six sub factors: the length of pipeline X_1, the diameter of pipeline X_2, the roughness of pipeline X_3, the velocity of oil flow X_4, electrical resistivity of oil flow X_5 and kinematic viscosity X_6.

6 groups of experiments were carried out with the same volume of oil at the same ambient temperature and humidity. In order to ensure the accuracy of the experiment, the residual and the independent variables should be consistent in addition than those 6 sub-factors are not the same. The types and characteristics of oil pipeline in the 6 experimental groups are selected as follows:

(1) kerosene sample (the electrical resistivity of $2.14\times10^{11}\Omega$•m, kinematic viscosity of $2.37m^2/s$) travels at a flow rate of 2.44m/s through the length of 1.07m, diameter of 6.35mm, and surface roughness of 0.14mm smooth stainless steel tube;

(2) gasoline samples (the electrical resistivity of $2.50\times10^{11}\Omega$•m, kinematic viscosity $0.46m^2/s$) travels at a flow rate of 1.83m/s through the length of 1.22m, diameter of 9.53mm, and surface roughness of 0.19mm stainless steel tube;

(3) aviation kerosene sample (the electrical resistivity of $2.1\times10^{12}\Omega$•m, kinematic viscosity of $6.32m^2/s$) travels at a flow rate of 3.05m/s through the length of 1.37m, diameter of 12.7mm, surface roughness of 0.11mm clean carbon tube;

(4) kerosene sample (the electrical resistivity of $2.14\times10^{11}\Omega$•m, kinematic viscosity of $2.37m^2/s$) travels at a flow rate of 3.66m/s through the length of 1.52m, diameter of 6.35mm, and surface roughness of 0.29mm rusted carbon steel pipe;

(5) gasoline samples (the electrical resistivity is $2.50\times10^{11}\Omega$•m, kinematic viscosity $0.46m^2/s$) travels at a flow rate of 2.13m/s through the length of 1.68m, diameter of 9.53mm, and surface roughness of 0.19mm rough stainless steel tube;

(6) aviation kerosene sample (the electrical resistivity is $2.1\times10^{12}\Omega\cdot m$, kinematic viscosity for $6.32m^2/s$) travels at a flow rate of 4.57m/s through the length of 1.83 m, diameter of 12.7mm, and surface roughness of 0.14mm smooth stainless steel tube. These 6 groups of tests were conducted according to the combination of the above schematic diagram, and the measurements of the electrostatic current were recorded in each group.

2.3 Experimental results

According to procedures mentioned above, six groups of experiments were carried out, and the measurements were recorded. The testing data are showed in table 1.

Table 1: Experimental data

Experimental number	Length of pipeline X_1/m	Diameter of pipeline X_2/mm	Roughness of pipeline X_3/mm	Velocity of oil flow $X_4/m\cdot s^{-1}$	Electrical resistivity of oil flow $X_5/10^{11}\Omega\cdot m$	Kinematic viscosity of oil flow $X_6/m^2\cdot s^{-1}$	Electrostatic current $X_0/10^{-10}A$
1	1.07	6.35	0.14	2.44	2.14	2.37	479.1
2	1.22	9.53	0.19	1.83	2.5	0.46	249.8
3	1.37	12.7	0.11	3.05	21	6.32	364.7
4	1.52	6.35	0.29	3.66	2.14	2.37	320.4
5	1.68	9.53	0.19	2.13	2.5	0.46	252.4
6	1.83	12.7	0.14	4.57	21	6.32	585.2

3. Methodology of Generalized Gray Incidence Model

Recently, analysis of impact factors is mostly on a basis of the mathematical statistics such as the regression analysis, the variance analysis, the principal component analysis, etc. These methods, however, have the following shortcomings:

(1) Requirement of large amounts of data. Small amounts of data make it difficult to find out the statistical laws. (2) Requirement of typical distribution of samples. Such assessments require linear relationship between every factor and the system characteristic data, and factors are unrelated to each other.

(3) A lot of computation work. There is a large amount of mathematical operations which often need to be relied on computers.

(4) Quantitative results may not match the qualitative analysis. Such difference may result in distortion of relationships and laws in the system. In the actual analysis of impact factors, information is very limited due to the constraints of statistical data, and impact factors are uncertain or incomplete, which present in large degree of greyness. The distribution of data is often not typical as a result of disturbance in human factors, so it is difficult to analysis by those statistical methods.

Gray Incidence Analysis Model is a branch of the Gray system theory which is proposed by Professor Deng Julong. Then, Professor Liu Sifeng developed it to the Generalized Gray Incidence Model (Deng, 1985; Liu et al., 2011). The Generalized Gray Incidence Model is an analytical method not based on the statistical methods but on the grey theory, thus it is applicable to different amount and distribution of samples. What's more, it needs a few operations and the quantitative results will match the qualitative analysis well. It is an analytical method to find out the internal relationship through the grey relational grade and to discover the main connection and major factor. The basic idea of these two models is to judge whether the relationship between the two factors is close. The closer to the curve sequence, the greater the degree of incidence. This model is carried out by the following steps (Liu and Xie, 2013):

(1) The system characteristics and the related factors of behaviors sequence are set up to obtain the calculation for the Generalized Gray Incidence model. The right mapping quantity is selected from the eigenvector of behavior system, and then the impact factors are determined from the behavior system. The behavior sequence Xi is composed of No. k observation data xi(k) (k=1, 2, …, n) in the system, namely Xi=(xi(1), xi(2), …, xi(n)), i=1, 2, …, m.

(2) All data are normalized to the initialization processing. The initial value X_i' is to initialize or to non-dimensional calculate the behavior sequence X_i. The process is $X_i'= X_i/x_i(1)=(x_i'(1),x_i'(2),\ldots,x_i'(n))$, i=1,2,…,m. Where $x_i(1)\neq0$; $x_i(1)$ is called the initial value operator. After the initial value is determined, the reference object is selected to compose the reference sequence $X_0'=(x_0'(1), x_0'(2), \ldots, x_0'(n))$, i=1, 2, …, m, while the rest of the initial value composes the relative sequences.

(3) After data initialization, it is carried out data zero image processing to obtain the starting point data to obtain the correlation coefficient. Difference sequence shows the differences between two sequences. According to the reference sequence and relative sequence in the initial value X_i', the difference sequence is

obtained by subtracting the corresponding items from those two sequences, that is $\Delta_i(k)=\left|x_0'(k)-x_i'(k)\right|$. The difference sequence is $\Delta_i=(\Delta_i(1), \Delta_i(2), \ldots, \Delta_i(n))$, i=1, 2, …, m.

According to the comparison of the difference sequence, the maximum difference and the minimum difference are selected among the various differences. The maximum difference and the minimum difference reflect the maximum and the minimum value between two sequences. The maximum difference $M=\max_i \max_k \Delta_i(k)$, whereas the minimum difference

Bring the obtained maximum difference and minimum difference into equation (1) to calculate the grey relational coefficient.

$$r_i(k)=\frac{m+\xi M}{\Delta_i(k)+\xi M} \tag{1}$$

Where k =1, 2, …, n; i=1, 2, …, m; ξ for the resolution factor and $\xi \in (0,1)$, ξ is used to weaken the anamorphic influence caused by large value of the maximum difference.

(4) The results can be obtained from the Gray correlation degrees and their ranking table. The grey relational grade r_i reflects the relation degree between the reference sequence and the relative sequences, and it can be obtained from equation (2):

$$r_i=\frac{1}{n}\sum_{k=1}^{n} r_i(k) \tag{2}$$

Where i=1, 2, …, m. The grey relational grade between the two sequences can be reflected by r_i, while the value of r_i shows the mutual influence of those two sequences. The bigger the greater.

In the system analysis, the size of the sub-factors between the order is the focus of research. From the overall study of the numerical value of a single correlation degree, there is no practical significance.

4. Data analysis based on Generalized Gray Incidence Analysis

The data initialization of Generalized Gray Incidence Analysis is showed in table 2. Due to the different experimental data between various physical quantities, the dimensions of factors are not identical. If it is directly calculated, the role of certain factors will be exaggerated or reduced. Therefore, the data first need to non-dimensional processing to convert data from table 2 to table 3.

Step 1: Data processing

Table 2: The initialization of the data

Experimental number	Length of pipeline X_1/m	Diameter of pipeline X_2/mm	Roughness of pipeline X_3/mm	Velocity of oil flow X_4/m•s^{-1}	Electrical resistivity of oil flow X_5/10^{11}Ω•m	Kinematic viscosity of oil flow X_6/m^2•s^{-1}	Electrostatic current X_0/10^{-10}A
1	1	1	1	1	1	1	1
2	1.14	1.5	1.36	0.75	1.17	0.19	0.52
3	1.28	2	0.79	1.25	9.81	2.67	0.76
4	1.42	1	2.07	1.5	1	1	0.67
5	1.57	1.5	1.21	0.87	1.17	0.19	0.53
6	1.71	2	1	1.87	9.81	2.67	1.22

Step 2: Data zero image processing

Table 3: Starting point data

Experimental number	Length of pipeline X_1/m	Diameter of pipeline X_2/mm	Roughness of pipeline X_3/mm	Velocity of oil flow X_4/m•s^{-1}	Electrical resistivity of oil flow X_5/10^{11}Ω•m	Kinematic viscosity of oil flow X_6/m^2•s^{-1}	Electrostatic current X_0/10^{-10}A
1	0	0	0	0	0	0	0
2	0.14	0.5	0.36	-0.25	0.17	-0.81	-0.48
3	0.28	1	-0.21	0.25	8.81	1.67	-0.24
4	0.42	0	1.07	0.5	0	0	-0.33
5	0.57	0.5	0.21	-0.13	0.17	-0.81	-0.47
6	0.71	1	0	0.87	8.81	1.67	0.22

Step 3: Calculation of correlation coefficient

$\left|s_0'\right|$=1.63 , $\left|s_1'\right|$=1.77 , $\left|s_2'\right|$=2.5 , $\left|s_3'\right|$=1.43 , $\left|s_4'\right|$=0.81 , $\left|s_5'\right|$=13.55 , $\left|s_6'\right|$=0.89

$\left|s_1'-s_0'\right|$=3.175 , $\left|s_2'-s_0'\right|$=3.910 , $\left|s_3'-s_0'\right|$=2.840 , $\left|s_4'-s_0'\right|$=2.215 , $\left|s_5'-s_0'\right|$=14.965 , $\left|s_6'-s_0'\right|$=2.295

$\left|s_0'\right|$ means self characteristic parameter of X_0, $\left|s_1'-s_0'\right|$ means the relative difference between X_1 and X_0's own characteristic parameters. The meanings of the other parameters are similar to that.

Step 4: Gray correlation degree calculation and ranking

γ_{01}=0.581, γ_{02}=0.567, γ_{03}=0.588, γ_{04}=0.608, γ_{05}=0.519, γ_{06}=0.605

so $\gamma_{04}>\gamma_{06}>\gamma_{03}>\gamma_{01}>\gamma_{02}>\gamma_{05}$

The correlation coefficient above expresses the relationship between the factor X_1 and factor X_0, and the other parameters are similar to such meaning.

By the above calculation, it is found that the value of γ_{04} is the largest, which shows that the relationship between the sub-factor X_4 (oil flow velocity) and the parent factor X_0 is the most closely, and the correlation degree between the residual factor and the parent factor is the same as the numerical value.

5. Conclusions

(1) From the correlation degree of the ranking, it can be seen that the value of factor X_4 is largest, which means the sub-factor X_4 and the parent factor X_0 is the most closely related factors, that is, the velocity of oil flow is the most important factor in the electrostatic generation. Therefore, the oil flow rate should be strict control in the process of upload and download. When the velocity of oil flow is large, some safety method should be applied to avoid producing of a static spark and to prevent explosion. At the same time, factor X_6 is the second largest one in all factors, which shows that the kinematic viscosity of oil is also a key factor contributed to the electrostatic generation. When the pipeline transportation involves some high viscosity oil such as aviation kerosene, it is required to the application of some electrostatic elimination measures to prevent the occurrence of static electricity accident.

(2) In this paper, simulative experimental system is established to measure electrostatic in the pipeline flow. The Generalized Gray Incidence Analysis Method is used in the analysis of multi factors causing electrostatic current in pipeline flow, and combined with the experimental data, the most critical factor is found out from gray relational analysis. This model is proved feasible, and correlation between many factors which produce static electricity is obtained through rigorous quantitative analysis. Through the analysis of the key factors, it is obtained to the electrostatic influence mechanism and the control mode in the process of oil pipeline transportation, which also presents guidance for safety protection of oil pipeline.

(3) This paper only considers six factors of electrostatic generation in the pipeline flow. However, other factors which are related to electrostatic such as moisture, temperature, filters and filter separator, etc, is beyond the research due to the lack of measurement conditions or experiment equipment. In the next step, a detailed study of those factors in the experiment should be considered, it is also required to improve experimental device to a higher precision, and the number of experimental groups should be increased to get more accurate conclusions.

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