A Framework for Detecting the Self-heating Source in Oil Tank

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Abstract: In this paper, a framework for finding out hot source of spontaneous combustion due to oxidation exothermic in oil tank is introduced. Spontaneous combustion in the Oil tank has become one of the most serious safety problems that affect the sustainable development of economy owing to the amount of stored crude oil increased with the development of the petroleum industry. In order to achieve a more efficient approach to detect accurately self-heating source in oil tank, the framework of detection system was proposed based on infrared detection instrumentation. Firstly, self-heating experiments of ferrous sulfide confirmed that there was a typical exothermic reaction, and when the temperature reached at about 340 degrees Celsius, the maximum rate of temperature has been rising. After that, a numerical model for analyzing the heat transfer effect on the tank was built, which took evident relationship between oil tank inside and outside. The results show that there exists the temperature difference from the center to the surrounding on the surface of the tank where oxidation exothermic reaction has been occurred. Therefore, the research achievements of the framework for detecting the self-heating source in oil tank can provide the sufficient basis to the design and construction of the detection system. Copyright © 2013 IFSA.

Keywords: Self-heating, Detection, Infrared Technique, Oil tank.

1. Introduction

Generally speaking, current production of crude oil contains both active sulfur and non-active sulfur, and reacting directly with metals are defined as active sulfur, as well contain elemental sulfur, hydrogen sulfide, low molecular weight thioalcohols and so on. Active sulfur can corrode iron material in many ways [1, 2]. Wet hydrogen sulfide at low temperature can react with corrosion products Fe₂O₃ to form ferrous sulfide. Ferrous sulfide was found to be self-ignited in 1826, i.e., pyrite mineral ore and coal with ferrous sulfide self-ignited easily [2]. Self-ignition has become one of the most serious safety problems in the oil tank. Self-ignition is combustion under natural conditions, which mainly develop through the process of spontaneous combustion and is frequently triggered by activity of depositing and taking the oil. Self-ignition is caused by the exothermic reaction becomes self-accelerating until combustion occurs. By the late twentieth century, as the amount of stored crude oil increased with the development of the petroleum industry, the corrosion tendency of petroleum processing, storage and transportation facilities became greater. Many accidental explosions and fires in oil tanks occurred around the world [2, 3].

Because of these problems, many researchers in different countries have devoted considerable effort investigating the mechanism, prediction, and
extinguishing of fires in oil tanks. People thought the accidents were the result of spontaneous ignition involving ferrous sulfide, which was a corrosion product of oil tanks. Considerable results have been achieved over the past years, in such areas as an understanding of the chemical thermo-dynamical and electrochemical mechanisms, Self-ignition potential tests, oxidation suppressants, ventilation, relevant measures, etc. A further simple and commonly used approach is to analyze temperature anomalies recorded at the near-surface of oil tank. However, little attention has been paid to the processes causing temperature anomalies at the surface, which plays a dominating role in the process of prevention of Self-ignition. Temperature anomalies analyze is one of the most complex subjects in the detection of fire source.

There are a variety of test methods currently in use for detection of open fires and spontaneous combustion (SC) based on temperature measurement methods [4-8]. As one of them, the infrared technique (IR technique) has many advantages over the thermocouple technique. First of all, the IR technique is a non-intrusive, i.e., no physical contact with the heat source is attained so there is no adverse effect on the temperatures and devices. In other words, the IR technique does not interfere with the flow of heat like thermocouples do. Second, the IR technique has a very fast response, making it a very useful instrumentation in temperature measurement. The disadvantage of the IR technique is that the exact surface emissivity should be known in order to make an accurate measurement. Knowing the exact surface emissivity is a function of surface temperature, surface roughness and possible phase transitions. Including some problems still exit about how to detect fire source. Considering the oil tank as a large volume containing a thermal source which maintains a constant temperature on one moment in time and covered by tank, some information about fire source will be given feedback to its surface when the oil tank with SC tendency emits infrared radiation. In this paper, the aim of this research is to present a new approach to detect SC of oil tank based on the IR scanning system.

2. Mechanism of SC in Oil Tanks

Some hydrogen sulfide of oil and trace one of vapor space will corrode tank that is long-term used. For the reason that, a layer of glial membrane, that is of a certain thickness, strong flexible, will be taken shape by ferrous sulfide generation and oligomers or grease come from inside of the tank, and attached to the tank wall. The mixture of ferrous sulfur colloid have been easily accumulated in the bottom of the tank, floating-disc, breathing-holes, tank walls and other parts of the tank with the internal floating roof moving up and down.

According to the literature [2], the unreacted iron in inside layers is exposed to crude oil the anticorrosion layers applied in oil tanks deteriorated in certain small areas because of long time use and action of corrosion. With a thin film of water on the surface of iron, CO₂ and H₂S in oil tanks are dissolved in water film to make it acidic. When iron is oxidized to Fe²⁺ with the water film, it generates electrons which are transferred to the cathode; H₂ is released as the result of bonding of H⁺ and the electron. Fe²⁺ in the water film reacts with OH⁻, which is derived by hydrolysis, to form Fe(OH)₂. The reaction formulae are as follows:

\[ \text{Fe} + 2\text{H}_2\text{S} \rightarrow \text{FeS} + \text{H}_2, \quad (1) \]

\[ 2\text{FeS} + 7/2\text{O}_2 \rightarrow \text{Fe}_2\text{O}_3 + \text{SO}_2 + 370.02\text{KJ}, \quad (2) \]

2.1. SC Characteristics of Ferrous Sulfide

The self-heating property of ferrous sulfide can reflect their propensity to spontaneous combustion directly. Therefore, 40~300 mesh (0.05~0.45 mm) ferrous sulfide were taken as experiment subjects to test by our laboratory bench modified, as shown in Fig. 1.

![Fig. 1. Schematic diagram of self-heating laboratory bench.](image)

1-Poisonous gas absorption bottle; 2-Stent; 3-sample of ferrous sulfide; 4-Slot model; 5-Automatic heating incubator; 6-Enclosing cover; 7-Temperature probe; 8-Humidifier; 9-Flow meter; 10-Buffering bottle; 11-Automatic temperature recorder; 12-Oxygen cylinder.

![Fig. 2. Self-heating curve of sample of ferrous sulfide (0.05~0.45 mm).](image)
Fig. 2 shows the self-heating curve of ferrous sulfide which is range from 0.05 mm to 0.45 mm. From the curve trend, there is a typical exothermic reaction. When the temperature reach to about 340 degrees Celsius, the maximum rate of temperature rising. The iron sulfide compounds reacts with oxygen in the air and an exothermic reaction occurs, even in ambient conditions. A problem arises when the rate of heat release produced by this process is more than is dissipated by heat transfer to the surroundings. The heat of reaction accumulates, the reaction becomes progressively faster, and thermal runaway take place to the point of ignition.

3. Thermal Modeling of SC

3.1. Assumed Process

To analyze the influence of involved physical and chemical processes to resulting temperature anomalies along the surface of tank, thermal modeling of SC has been performed with partial differential equation of heat conduction [9]. For reasons of simplicity, the following assumptions are made:
1) The tank surrounding fire source is homogeneous and isotropic.
2) The area of fire source is small and the distance from the fire source to the tank surface is much longer than the size of the fire source, which can be considered as a point fire source.
3) The heat convection inside tank is ignored.

Fig. 3 presents the processes and heat transport mechanisms used here. It can be considered an internal heat source heat exchange with peripheral walls are divided into two processes, including the heat transfer between heat source and its surrounding walls and the heat convection between walls and atmosphere. Heat-exchange diagram as shown in Fig. 3.

![Diagram of detection and energy flows in the area of fire source.](image)

3.2. Thermal Modeling

The thermal resistance of the tank heat transfer conduction and surface heat convection are \( R_1 \) and \( R_2 \). Among them [8]:

\[
R_i = \frac{1}{2 \pi \lambda} \ln \frac{d_i}{d_0} = \frac{t_{i0} - t_{i1}}{Q} \quad (3)
\]

\[
R_2 = \frac{1}{\pi d_i \lambda a} t_{i0} - t_{f1} \quad (4)
\]

The total thermal resistance of heat transfer is equal to the sum of the tank thermal resistance of heat conductive and convective heat transfer surface of the tank. That is:

\[
R = R_1 + R_2 = \frac{1}{2 \pi \lambda} \ln \frac{d_i}{d_0} + \frac{1}{\pi d_i \lambda a} \quad (5)
\]

where \( d_0 \) is the diameter of the heat source, m; \( d_i \) is the distance from heat source center to a certain point \( i \) in the surface of the tank, m; \( t_{i0} \) is the ignition temperature, \( ^\circ C \); \( t_{f0} \) is the temperature of a certain point \( i \) in the tank surface, \( ^\circ C \); \( t_{f1} \) is the tanks surrounding environment temperature, \( ^\circ C \); \( \lambda \) is the tank material coefficient of heat conductivity, W/m\(^\circ C\); \( a \) is the coefficient of air convection heat transfer, W/m\(^2\)\(^\circ C\); \( l \) is the length of heat source, m.

According to Eqns. (3) and (5), capacity of heat transmission is:

\[
Q = \frac{t_{f0} - t_{f1}}{\frac{1}{2 \pi \lambda} \ln \frac{d_i}{d_0} + \frac{1}{\pi d_i \lambda a}} \quad (6)
\]

According to Eqns. (5) and (6), the surface temperature distribution and storage tank temperature difference can be calculated:

\[
t_{i0} = t_{f0} - \frac{Q}{2 \pi \lambda} \ln \frac{d_i}{d_0} = t_{f0} - \frac{(t_{f0} - t_{f1}) \ln \frac{d_i}{d_0}}{\ln \frac{d_i}{d_0} + \frac{2 \lambda}{d_i \lambda a}} \quad (7)
\]

\[
\Delta t_{j(i)} = \frac{(t_{f0} - t_{f1}) \ln \frac{d_i}{d_0} + \frac{2 \lambda}{d_i \lambda a}}{\ln \frac{d_i}{d_0} + \frac{2 \lambda}{d_i \lambda a}} \quad (8)
\]

3.3. Temperature Difference Identification of Surface on Tank

As the Eqn. (8) shows, the heat source heat transfer to the tank surface exist the difference in temperature, which lead to the tank surface temperature field change. Simulated oil tank field conditions, taking \( t_{f0} \) is 4.3 °C, around common wind speed \( v \) is approximately 3.1 m/s. According to empirical formula \( a=1.163+(10+6v^2) \) [10]. Calculating the convective heat transfer coefficient is 23.92. Thermal conductivity coefficient takes as 0.036 W/m\(^\circ C\) and diameter of fire takes as \( d_0=0.2 \)
The list of parameters for calculation can be seen in Table 1.

Table 1. The list of parameters for calculation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank surface temperature ( t_f )/°C</td>
<td>4.3</td>
</tr>
<tr>
<td>Around common wind speed ( v )/(m/s)</td>
<td>3.1</td>
</tr>
<tr>
<td>The convective heat transfer coefficient</td>
<td>23.92</td>
</tr>
<tr>
<td>Thermal conductivity coefficient ( (W/m·°C) )</td>
<td>0.036</td>
</tr>
<tr>
<td>Diameter of fire source ( d_0/)m</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Fire source was taken as different depth distance to calculate the distribution of the tank surface temperature. As shown in Fig. 4, the higher temperature of the fire source is, the higher temperature away from its closest tank surface. With the probing depth increases, its surface temperature difference is less, which is according with practice, when the deeper of fire source location, the more hidden it is, which will increase the difficulty of detection.

![Fig. 4. Temperature distribution on the surface of tank with the increasing of the detecting depth.](image)

From the temperature curve of different temperature fire source in Fig. 4, it can be found that the higher temperature of the fire source, the faster changer of temperature curve. When the probing depth increased, the existence possibility of detecting fire in theory, but which would increase the requirement of detection system.

And there exists the difference in temperature from the center to the surrounding, on the surface of the tank which contains a spontaneous combustion fire. What’s more, both the theoretical derivation and the numerical simulation represent that, the tank which contains a spontaneous combustion fire will necessarily form a characteristic temperature distribution on the surface. As long as the chosen fire prospecting instrument will be able to survey the characteristic of temperature distribution on surface, the detection of the spontaneous combustion of tank fire will be possible.

### 4. Detection Technology

#### 4.1. Principle of the Infrared Detection Technology

Fire detection technology of infrared technique can scan tank surface temperature field distribution by infrared thermometer, and then obtain temperature field information of tank according to the anomalies of surface temperature distribution.

The principle of the infrared detecting technique is that, when temperature of object is under absolute zero, it will make molecular vibration, radiates infrared electromagnetic waves automatically. It is well known that light has wave characteristics, and according to different wavelengths, they are ‘UV’, ‘visible’ and ‘infrared light’ three categories. The wavelength ranges from 350-700 nm which can be seen is "visible light". Higher than the 700nm part is the ‘infrared’, less than 350 nm part is ‘Ultraviolet’, and the 700-1000 nm light wavelength is called ‘near-infrared light’. The human eye can not observe infrared light, but the CCD camera can, as CCD's characteristics decide its perception of near-infrared light ability is better than the human eye, ‘color to black’ camera is the one that use CCD camera with near infrared light good perception, which can run 24-hour all-weather surveillance by IR lighting, consequently leading to covert monitoring at night. But in reality there will be clear during the day time and blurred picture in the night. The radiation energy is as follows:

\[
E = \varepsilon \sigma T^4, \tag{9}
\]

where \( \varepsilon \) is the radiation coefficient, \( 0<\varepsilon<1 \), it is affected by chemical component, external status, and so on; \( \sigma \) is the Stefan-Boltzman constant, \( \sigma = 5.67 \times 10^{-8} \text{W/(m}^2\text{·K}^4) \).

Object which radiating out heat will also absorb heat energy from surrounding objects. The different between energy radiating out and absorbing in is the net energy radiate out. According to Stefan-Boltzman Law, object’s radiation power will increase rapidly when temperature increase.

From the simplified Mathematical model previous described, under the same temperature, the radiation energy of different objects are affected by radiation coefficient, and the radiation energy field is different. For the same object, the higher its temperature is, the stronger its radiation energy field is. The radiation
energy field has energy and direction, so when the oil tank radiates infrared waves, the related information of the spontaneous combustion in the tank can be fed back to surface on the form of field.

4.2. Deciding the Detection Region

Decide the detection region, lay the detection spots, the interval between two spots are commonly 0.25-0.50 m according to the actual requirement. Schematic of laying the detection spots is shown in Fig. 5.

4.3. Determining the Position of the Concealed Spontaneous Fire in the Oil Tank

According to the mechanisms of SC in oil tanks, CO₂ and H₂S in oil tanks are dissolved in water film to make it acidic, when iron is oxidized to Fe²⁺ with the water film, it generates electrons which are transferred to the cathode; H₂ is released as the result of bonding of H⁺ and the electron. Fe²⁺ in the water film reacts with OH⁻, which is derived by hydrolysis. All the reactive pathways are exothermic processes. So the anomalies of surface temperature distribution in tank can be acquired by infrared thermometer.

The purpose of infrared scanning in the tank surface is to confirm the position and height of spontaneous combustion of tank effectively according to the capacity of infrared radiation. In fact, the problem like estimation of heat source in heat conduction problem from temperature measurement is typical inverse heat conduction problem (IHCP). One main characteristic of heat conduction problem is that its mathematical definite solution sometimes is improperly-posed and very difficult to solve. The intensity of tank spontaneous combustion is closed to the depth of fire source and temperature difference on the oil tank surface, which is the next step of work.

5. Detection System Design

To be considered the actual situation of field and complex features of hot source position, the detection system was designed to follow the principles of real-time imaging and carrying easily. The framework of the overall structure was shown in Fig. 6. Computer processing system is mainly responsible for showing infrared images, pseudo-colour conversion, image storage and analysis functions with real-time. After collecting the IR imaging signal, then we can transmit the IR imaging signal to the computer, and use the powerful data processing of portable computer to take on a variety of online image processing and improving image quality. And we can store the image at any time, for the purpose of facilitating offline treatment.

6. Conclusions

Surface temperature of oil tank is an important parameter in judging its oxidation and self-heating velocity and the temperature can be further used to forecast the its self-ignition. So temperature measurements remain an attractive approach to investigate self-ignition of oil tank and detect its fire source position using advanced equipments.
thermometer can be used to measure the surface temperature on the tank, and the further judgment can be attained according to the calculation of IHCP.

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