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Expanded Perlite Insulation Settlement Monitoring Technology of Large LNG Storage Tank

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***Abstract*—Nowadays, the expanded perlite as the cryogenic insulation material is widely used in LNG storage tank. And the settlement of expanded perlite will affect the safe operation of the cryogenic system. On the basis of the large cryogenic LNG storage tank, a settlement monitoring method based on distributed fiber optic of insulation materials is put forward in the paper. The locations of distributed fiber optic are determined and the threshold of monitoring system is investigated. Besides, other factors impacting the temperature of insulation layer are also discussed. Finally, it is confirmed that the monitoring program is effective by numerical simulation and theoretical calculation.**

Keywords-LNG storage tank; expanded perlite insulation settlement; distributed fiber optic measurement; structural health monitoring

I. INTRODUCTION

In order to reduce the conduction of heat between the cryogenic system and the external environment, the wall of LNG storage tank is filled with expanded perlite insulation material. Cold insulation performance directly affects the BOG energy consumption. And evaporating gas will increase the tank pressure at the same time, which directly affects the safe operation of the tank. On the basis of analysis of failure mode and the identification of key point on cryogenic system, this paper takes expanded perlite as the core, establishing reasonable monitoring points, detection parameters, evaluation methods, etc. Finally, a complete monitoring scheme for expanded perlite insulation settlement is formed.

II. PRINCIPLE FOR BUILDING SETTLEMENT MONITORING SYSTEM

The settlement of expanded perlite will change inner temperature of cryogenic insulation systems. Therefore, the location of settlement can be detected by monitoring the temperature of insulation layer. Distributed optical fiber temperature measurement technology is able to monitor settlement of cryogenic LNG storage tank insulation system in real time and on-line. Besides, it overcomes the drawbacks of traditional measurement, which is not reliable in the low temperature. The principle of distributed optical fiber temperature measurement technology is the laser propagated in the fiber could reflect and scatter if the change occurs somewhere in the fiber. Wherein a portion of the scattered light will be collected by the receiver, the change of temperature can be detected by using light-domain reflection principle. Then position of settlement can be acquired.

When the laser propagates in the medium, electrons will be stimulated as forced vibration, thus diffusing coherent waves. One of the reflections is called Raman scattering.

Raman scattered light is produced by fiber thermal vibration of molecules interacting with photons and exchanging energy. If a portion of the light energy is converted into thermal vibration, it will diffuse a longer wavelength than the source of light called Stokes light; while if a portion of thermal vibration is converted into the light energy, it will diffuse a shorter wavelength than the source of light called Anti-Stokes light. Raman scattered light is composed of the two different wavelengths of light, as shown in Fig. 1. The offset of wavelength is determined by the fixed attributes of optical fiber.

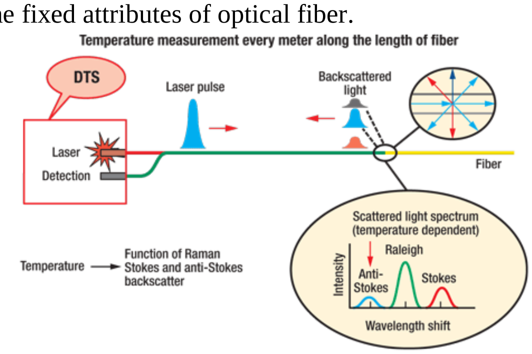

Figure 1. Raman optical time domain reflector diagram

It is found that Anti-Stokes scattered light is sensitive to temperature while Stokes scattered light is substantially independent of temperature. However, when Anti-Stokes scattered light is used to detect temperature, some factors such as the instability of the incident optical power, fiber bending and compressing will affect the size of Anti-Stokes backscattered optical power. In order to eliminate these adverse effects, Stokes scattered light is used as a reference channel. By detecting the backscattered optical power ratio, temperature information in the scattering region can be demodulated. If the energy of incident light into the fiber is E_0; the incident velocity is v; the length of fiber is L; Stokes backscattered light power is:

$$P_s(T)=\frac{v}{2}E_0K_s\exp\left[-(\alpha_0+\alpha_s)L\right]R_s(T) \tag{1}$$

Anti-Stokes backscattered light power is:

$$P_{as}(T)=\frac{v}{2}E_0K_{as}\exp\left[-(\alpha_0+\alpha_{as})L\right]R_{as}(T) \tag{2}$$

Where: K_s, and K_{as} are Stokes and Anti-Stokes scattered coefficients per unit length along the fiber respectively; α_0, α_S, and α_{as} are transmission loss in the optical fiber of incident light, Stokes scattered light and Anti-Stokes scattered light respectively. $R_S(T)$, and R_{as} are temperature-dependent coefficients of Stokes scattered light and Anti-Stokes scattered light respectively.

Denoting

$$\begin{aligned} f(T)&=P_{as}(T)\ /P_s(T)\\ &=\frac{K_{as}}{K_s}\exp(-h\Delta v\ /kT)\exp\left[-(\alpha_{as}-\alpha_s)L\right] \end{aligned} \tag{3}$$

When $T=T_0$:

$$\begin{aligned} f(T_0)&=P_{as}(T_0)\ /P_s(T_0)\\ &=\frac{K_{as}}{K_s}\exp(-h\Delta v\ /kT_0)\exp\left[-(\alpha_{as}-\alpha_s)L\right] \end{aligned} \tag{4}$$

Denoting

$$\frac{1}{T}=\frac{1}{T_0}-\frac{k}{h\Delta v}\left[\ln\frac{f(T)}{f(T_0)}\right] \tag{5}$$

Since

$$2L=vt=Ct/n \tag{6}$$

Where: C is the propagation speed of light in vacuum, n is the refractive index of the optical fiber, v is the propagation speed of light in the fiber, t is the time of scattering.

The energy of the scattered light is

$$dE_r(2L)=K\beta E_0\exp(-2\alpha L)dL \tag{7}$$

Where: α is the light loss coefficient per unit length, K is scattered coefficient per unit length, β is the scattered factor. The backscattered optical power is

$$P(t)=\frac{v}{2}K\beta E_0\exp(-\alpha vt) \tag{8}$$

The scattered light power is a function of time; therefore, the position is a function of the scattered light power. Using this principle position of the fiber scattering can be acquired accurately.

III. ESTABLISHING MONITORING SETTLEMENT SYSTEM

A. *Finite Element Simulation on the Heat Leakage of Storage Tank*

Based on ANSYS software, a finite model of LNG storage tank is built to analyze heat transfer process on various parts of the tank. Since the tank is an axially symmetrical structure and the size is very large, for the purpose of easier calculation, the model is simplified as a 2D symmetric model, as shown in Fig. 2.

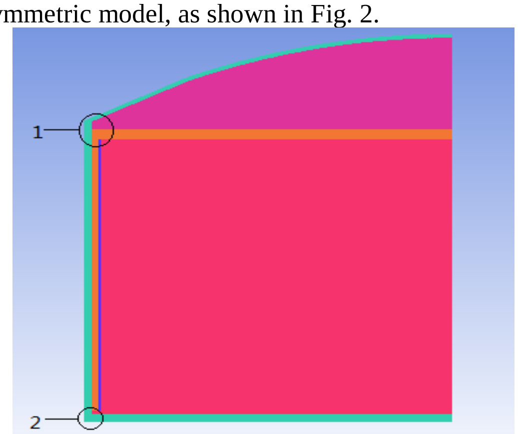

Figure 2. 2D model of LNG storage tank

The temperature distribution of the insulation layer is shown in Fig. 3.

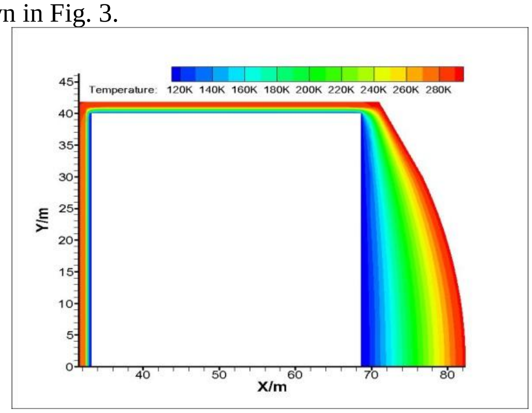

Figure 3. Temperature distribution diagram of insulation layer

It's conducted that the temperature gradient between the inner and outer surfaces of concrete layer is small, while the temperature gradient between inner and outer surfaces of expanded perlite insulation is relatively large by analyzing the temperature distribution of insulation layer. This also explains that the expanded perlite has a very good cold effect on LNG storage tank.

B. Theoretical Calculations on the Temperature of Insulation Layer

The main form of heat leakage of the cryogenic insulation system is environment importing heat through insulation material. Assumed the contacts between the layers of insulation material are good, without considering the contact thermal resistance, environmental heat importing into the tank is

$$\Phi=\frac{\Delta T \pi L}{\frac{1}{hd_1}+\sum\frac{1}{2\lambda_{3i}}\ln\frac{d_{i+1}}{d_i}} \tag{9}$$

Where: h is the heat transfer coefficient; λ is the thermal conductivity; d_i and d_{i+1} are the tank diameters of each layer; ΔT is the temperature difference between environment and cryogenic insulation system; L is the height of the tank.

Since the heat through the insulation layers is equal

$$\Phi_1=\frac{\lambda \Delta T A_w}{\delta_h} \tag{10}$$

Where: δ_h is the thickness of the insulation material; A_W is the area of the insulation material. Then the temperature of each insulation layer is available. BOR means evaporated gas mass percentage of total LNG quality in a day, which is calculated as

$$\mathrm{BOR}=\frac{24\times 3600\times\phi}{\gamma\rho V}\times 100\% \tag{11}$$

Where: γ is the latent heat of vaporization of LNG; V is the volume of the tank; ρ is the density of LNG. The theoretical calculation of the BOR is 0.04%, while the numerical simulation result is 0.042%. The two results are in good agreement, and the result is valid.

The temperature of insulation layer is mainly determined by the following factors: the thermal conductivity, internal and external temperature of LNG storage tank, convective heat transfer. The thermal conductivity is increased by the settlement of expanded perlite, so it is the focus of the monitoring system. The following parts discuss the temperature of insulation layer caused by these factors.

C. Thermal Conductivity Affecting Temperature of Insulation Layer

There will be settlement occurred in the service process because expanded perlite is a kind of particulate material. The settlement will increase thermal conductivity, thus changing the temperature of insulation layer. Table 1 shows the results of calculating the temperature of insulation layer at different multiples of expanded perlite thermal conductivity.

TABLE I. TEMPERATURE OF INSULATION LAYER UNDER DIFFERENT THERMAL CONDUCTIVITY (K)

Insulation Materials	Thermal Conductivity		
	1 multiple	*2 multiples*	*3 multiples*
Elastic fiber	163.8	263.4	284.4
Expanded perlite	183.5	252.1	281.1
Foam glass	193.8	246.2	279.4

It's shown in the table 1 that the temperature of perlite is sensitive to the thermal conductivity, that is to say, the temperature of perlite is sensitive to the settlement of expanded perlite.

When the thermal conductivity of expanded perlite increases by 2 or 3 multiples, BOR of the storage tank will be calculated as follows:

$$\mathrm{BOR}^{2'}=\frac{24\times 3600\times\phi^{2'}}{\gamma\rho V}\times 100\%=0.049\% \tag{12}$$

$$\mathrm{BOR}_3^{'}=\frac{24\times 3600\times\phi^{'}}{\gamma\rho V}\times 100\%=0.054\% \tag{13}$$

According to the relevant security requirements of LNG storage tank, when the BOR of the tank exceeds to 0.05%, cold performance of the LNG storage tank is no longer below threshold value. So the cold performance of the LNG storage tank will be seriously damaged even fail by the settlement of expanded perlite.

D. Temperature of Insulating Layer Related to the Temperature Field

The heat importing into cryogenic system is related to the LNG storage tank internal and external temperature. The environment temperature is varied, and there is temperature gradient on the external surface of the tank even at the same time. With the amount of LNG changing in the tank, the internal temperature field is unknown. The impact of temperature field on the insulation layer is discussed, and the results are shown in Fig. 4 and Fig. 5 respectively.

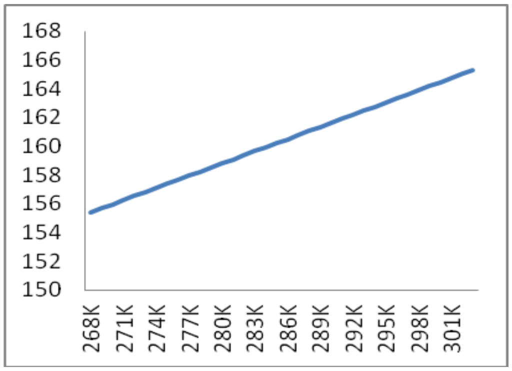

Figure 4. The temperature of perlite insulation changing with environment temperature

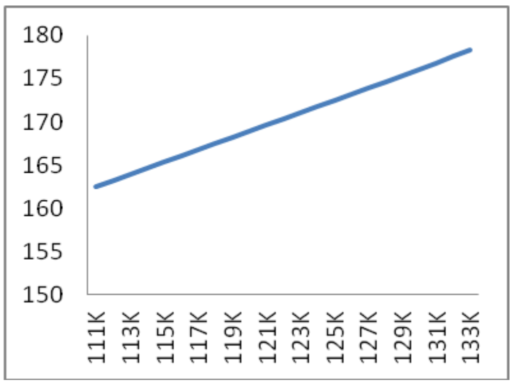

Figure 5. The temperature of perlite insulation changing with internal temperature field

According to the results, the temperature of perlite insulation changes with internal and external temperature. Therefore, in order to eliminate effects on the temperature of perlite insulation that internal and external temperature gradient brings, the monitoring system needs to monitor the internal temperature of the tank in real-time. Then the temperature of insulation material is calculated to compare with the collected temperature. If the threshold is reached, the settlement of perlite occurs.

E. Convection Heat Transfer Affecting the Temperature of Insulation Layer

The temperature of insulation layer is calculated at each different convection heat transfer coefficient. The results show that different convection heat transfer coefficients have a light effect on the temperature of insulation layer. So the effects on the temperature of insulation layer should be ignored when setting up distributed optical fiber temperature alarm threshold.

IV. METHOD FOR LAYING DISTRIBUTED OPTICAL FIBER

When the settlement of expanded perlite occurs, the thermal conductivity will increase, and the temperature of insulation layer will rise. Judging if the settlement of expanded perlite occurs by monitoring the temperature of perlite insulation is feasible. It should be noted that the distributed optical fiber needs to be firmly fixed, so as not to sink along with expanded perlite, causing unnecessary errors. Considering robustness and economy, the distributed optical fiber is distributed on crucial parts densely. About uncritical parts, the distributed optical fiber is laid only for the necessary connection. Based on the above considerations, the distributed optical fiber is wrapped around the inner wall of perlite insulation helically; the temperature field of internal tank is obtained by a vertical straight line distributed optical fiber. The interface is set on the top of the tank. At the top of the wall, the distributed optical fiber laying method is shown in Fig. 6.

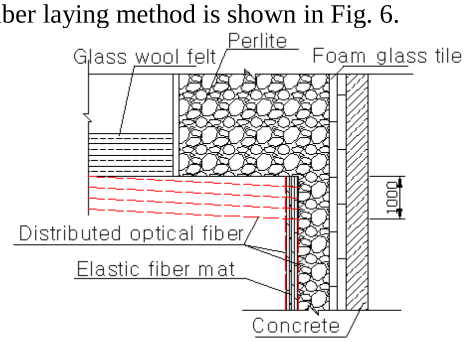

Figure 6. The locations of laying distributed optical fiber

The monitoring system can monitor the temperature of key parts in real-time. Double-ended measurement mode is used in the monitoring program. Two channels measure temperature from two directions with a fiber at the same time. Under this mode, when the fiber loop is in the presence of a power failure, it can still be measured on the circuit. Compared with single-ended measurement mode, it improves the reliability of the monitoring circuit.

V. CONCLUSIONS

A settlement monitoring system based on distributed fiber optic of insulation materials made of expanded perlite is put forward in this paper. The locations of distributed fiber optic are determined and the threshold of monitoring system is investigated. The following conclusions are drawn in the study: firstly, the heat leakage of LNG storage tank under normal operation is calculated theoretically and simulated numerically, and the two results are in good agreement. And it's verified that threshold of alarm of settlement monitoring system is reasonable. Secondly the settlement of expanded perlite will increase the thermal conductivity. Thereby the temperature of insulation layer will change. Furthermore, cryogenic insulation system will lose effectiveness. So real-time monitoring of the settlement is necessary. Finally, the temperature field will also affect the temperature of insulation layer. Therefore, the internal temperature of evaporation gas and the temperature of environment should be considered.

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