Measurement 58 (2014) 130–137

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Application of the fiber-optic distributed temperature sensing for monitoring the liquid level of producing oil wells

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ARTICLE INFO

Article history:
Received 22 December 2013
Received in revised form 27 June 2014
Accepted 1 August 2014
Available online 23 August 2014

Keywords:
Oil well
Liquid level
Optical fiber
Distributed sensing

ABSTRACT

In the process of petroleum exploitation, liquid level is a significant parameter to determine reasonable production of oil wells. In this paper a novel optical fiber based method is presented to monitor working liquid level of oil well which contains foam section. This method utilizes the principle of heat transfer variation in different medium and Raman optical scattering. A distributed temperature sensor composed of optical fiber and heating cable is proposed and can be placed in the casing–tubing annulus. According to the sudden variations of measured temperature, the interface of gas–foam, foam–liquid can be identified accurately.

1. Introduction

Various techniques are employed to maintain crude oil production at maximum levels within the life of an oil well [1]. The primary importance of these techniques is to force oil into the wellhead where it can be pumped to the surface. Enhanced oil recovery through the injection of CO2, preferably after water flooding, is one mechanism with which to recover more oil, extend the field life and increase the profitability of the fields. The basic concept is pushing CO2 into a field to extract more oil [2]. As a result, large volumes of gas are entered into crude oil and create a foam section in oil well. The foam section is lying above the liquid level and often has dozens of meters, sometimes even hundreds of meters. It leads to a great problem when monitoring the position of liquid level and estimating the pressure of well bottom.

In general, there are various methods and implementations for liquid level detection such as mechanical, capacitive, inductive, ultrasonic [3], acoustic [4] or optical [5]. From the previous reviews, it is concluded that optical fiber sensor is a promising candidate for harsh environment, high temperature, high pressure, corrosive/erosive, and strong electromagnetic disturbance. Recently, optical fiber sensors, with its glass nature and optical interrogation principle, may provide a viable solution for sensing and monitoring in these harsh environments and have found many applications in modern industry such as oil and gas extraction, power generation, coal gasification, and gas turbine operation [6]. In our previous work, optical fiber is utilized for real-time temperature and pressure monitoring in down-hole environment [7,8].

Recently, various approaches have been reported on fiber-optic liquid level sensor using Fiber Bragg Grating (FBG) [9–12]. But most of them need elaborate structures or utilize precise detection setup and are often applied in the area of fuel storage system and chemical processing.

In oilfield, the commonly used method in obtaining the liquid level is the acoustic method based on the reflection of acoustic wave. The principle of this method is to measure the distance to the liquid level in the casing annulus of a well. However, the foam section has strong sound absorption and low acoustic wave reflection. So it is difficult to measure the liquid level accurately with acoustic method if foam section existed. However, to author's knowledge, none of studies has been published so far to

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http://dx.doi.org/10.1016/j.measurement.2014.08.012

provide a method for monitoring working liquid level in those oil wells containing foam section. it is more difficult to measure the length of foam section and other important parameters.

In this paper, we propose a novel monitoring method combining heating cable and optical fiber. This method is based on the principle of Raman fiber scattering. A distributed temperature sensor system, based on a complex of optical fiber and auxiliary heating cable (COAH), is placed in casing-tubing annulus. When the heating cable generates heat, different medium have different responses to the temperature changing. This difference can be used to identify the interface between gas, foam and liquid section.

2. Operation principle and sensor fabrication

2.1. Overview of the liquid level monitoring method

Heating cable is a proven, reliable solution for industrial process temperature maintenance. It is widely used for applications including pipe tracing, freeze protection, viscosity control, temperature process maintenance etc. In our research, heating cable plays as heat source assisting the optical fiber to monitor the working fluid level of oil wells. The scheme of proposed monitor system is shown in Fig. 1. We bind the heating cable with the optical fiber sensor tightly and package them to form a complex. The distributed sensor is put into the tubing–casing annulus of oil well. Because of the obvious different characteristics of liquid, foam and gas in heat transferring, the measured temperature at the interface of gas–liquid or foam–liquid will differs considerably after heating for a period of time. The relation between heating time and temperature response of surrounding medium is derived using heat transfer theory. When the heating cable is on, different medium has different response to the temperature changing. This difference can be used to identify the interface between gas, foam and liquid section. It is known that Raman Optical Time Domain Reflectometer (ROTDR) only demodulated by the temperature. So we can utilize ROTDR to recognize the position of gas–foam level and foam–liquid level.

The downhole environment and condition are extremely harsh and the producing well could be kilometers long. So protective measures should be taken to prevent the optical fiber from being scuffed or corrode. In this research a kilometer long FRP (Fiber Reinforced Plastics) bar was fabricated by embedding one optical fiber. Several glass fibers were pulled from a pulley system, bathed in an epoxy basin, fed together with one or two OFs (Optical Fibers) at the center into the heating furnace, and finally pultruded through a rotating machine to form an FRP bar with embedded OFs as illustrated in Ref [13]. To realize the monitoring scheme in practical application, how to install the sensor in the tubing–casing annulus of oil well needed to be solved. The optical fiber sensor should be distributed vertically along the well. In this paper, a steel cable attached with a heavy object is used to solve this problem. The complex of optical fiber and heating cable is tighten and winded round the steel cable. Then the sensor could be installed along the well with the steel cable. A part of optical fiber is left on the ground for connecting to the Raman optical fiber demodulation device (DTS5100). This specific implementation of sensor setup process can ensure the vertical distribution of optical sensor and also eliminate the sensor weight's effect on the measurement precision and protect the sensor from damage.

2.2. Optical fiber Raman scattering based temperature measurement

2.2.1. Principle of optical fiber based space location

The distributed sensor is put into the tubing–casing annulus, and the quantitative relationship between the optical fiber monitoring point and the well's depth needs to be built. When laser pulse travels through the optical fiber, Raman scattering happens at every point in the optical fiber. Because scattering lights is isotropic, only partial scattering lights return along the optical fiber. If we set the start time as the laser pulse going into the optical fiber, the scattering echo signal that the input terminal receives at time t, indicates a distance of L from scattering point to the input terminal. And the laser pulses in optical fibers have traveled $2L$. The distance L can be expressed as $L = ct/2n$. Where c is the light speed in vacuum, n is the refractive index of optical fiber.

2.2.2. Distributed optical fiber Raman scattering temperature measurement theory

When the light travels through the optical fiber, the incident light's photons are scattered by the inelastic collision with optical phonons in the fiber. According to whether scattered light's wavelength is greater than the incident light's or not, the scattered light can be sorted as Stokes light and anti-Stokes light. Keeping the external parameters and the optical fiber parameters unchanged, there is functional relation between the temperature T at the monitoring position and the anti-Stokes light's optical power. Getting the anti-Stokes light's optical power at temperature $T = T_0$ and the back Stokes light's optical power at any temperature T, by dividing these two power, the temperature T can be written as:

$$T = \frac{h\Delta\upsilon}{k \cdot \ln\left[\frac{\exp(h\Delta\upsilon/kT_0)-1}{P_{AS}(T)} \cdot P_{AS}(T_0) + 1\right]} \tag{1}$$

where h is the Planck constant, $\Delta\upsilon$ is optical molecular vibration frequency, $P_{AS}(T_0)$ is the anti-Stokes light's optical power at temperature T_0, $P_{AS}(T)$ is the anti-Stokes light's optical power at temperature T.

If the initial temperature is known, temperature parameter can be gotten by the ratio of measured optical power. Then the influence caused by one optical fiber's intrinsic loss and defect can be eliminated with this ratio, which will bring a higher temperature measuring accuracy.

2.3. Heat-transfer model of COAH

The COAH contains the inner heat source, and the thermal conduction differential equation is given by: