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THE DEVELOPMENT OF A SENSOR SYSTEM FOR MONITORING THE DISPLACEMENT OF HORIZONTAL LATERALS IN RADIAL DRILLING TECHNOLOGY***

1. INTRODUCTION

Radial drilling is a technology that is meant to reach reserves that are not economically exploitable by means of conventional completion techniques (vertical, slanted, or horizontal wells), and which could also accelerate the recovery of hydrocarbon reserves. It is estimated that 70% to 85% of all known hydrocarbon discoveries remain in the ground, and for resources not amenable to secondary recovery techniques, a low cost targeted drilling system could prolong the life of a well. Radial drilling represents a family of through-pipe recompletion technologies for drilling horizontal channels out from an existing wellbores by making a 90 degree turn in a custom shoe, cutting through the casing and then deploying a flexible drill system. Systems using high pressure water at the end of coiled tubing have claimed to be able to reach 100 m away from the wellbore, leaving a channel of 25–50 mm in diameter.

Radial drilling could also be applied in wells when other stimulation techniques are not applicable, and on layers that are close to water-saturated layers which may limit the applicability of hydraulic fracturing stimulation.

Performance testing of these short radius laterals has not been adequately studied and it still has a number of weak points. The work detailed in this paper involves reviewing existing technologies for monitoring the displacement of horizontal laterals and proposing an innovative solution which could be make a good basis for future research.

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2. PROBLEM STATEMENT

Many oil and gas assets owned by small producers are mature oilfields with strong heterogeneities and substantial amounts of remaining hydrocarbons still in place, especially in the marginal low permeability formations, where production frequently becomes uneconomical. Enhanced oil recovery from these low permeability reserves is crucial to keep marginal wells profitable: additional reserves could be produced from these marginal reservoirs or strongly heterogeneous thick zones by diverting the flooding fluid to the formations enriched with residual oil or by creating additional drainage channels from the low-permeability zones of existing wells. Depending on reservoir formation and remaining oil distribution, there are a lot of challenges such as:

1) For thick, strongly heterogeneous zones, water sweep is mainly from the high permeability layer, leaving quite a large amount of remaining oil in the low permeability zone of the formation.
2) For multiple thin zones with interlayer sealing, oil displacement is proportional to the individual permeability so after years of production, remaining oil is left mainly in low permeability zones.
3) For low permeability marginal wells, oil productivity cannot be sustained at an economical level so a low-cost well stimulation approach must be deployed to maintain a certain productivity.
4) For low-permeability injection wells, fluid injection cannot meet the stimulation design requirements due to the large skin factor and limited injectivity.

To solve all of these problems we need to develop a reliable, accurate and cost-effective technology for reaching small remaining zones in a reservoir and monitoring the drilling bit at any time in the drilling process.

3. CURRENT STATE OF TECHNOLOGY

Hydro jetting perforations were first reported in 1939 but developed slowly over the following 50 years due to the limitations of material quality and the reliability of high-pressure pumps. In the late 1980s, coiled tubing and abrasion-resistant carbide jet-nozzles greatly improved this technology for production enhancement. In a hydro jetting drilling process, a casing-drilling machine is first deployed to drill a hole through the casing in an existing wellbore. Then, one or several slim laterals will be jet-drilled through a coiled-tubing running. It is believed that such a lateral-jet technology shows promise for recovering residual oil from marginal reserves by penetrating oil-enriched low-permeability formations and creating lateral holes in the hydrocarbon-enriched pockets that are left behind during waterflooding.

The process involves first pulling the production equipment, making up the deflector shoe, and running tubing to the desired lateral depth. Next, the milling assembly is run into the hole to create a hole through the existing casing. Afterwards, the jetting assembly is installed and run into the well to the deflector shoe. Once the jetting nozzle enters the pilot hole that was started with the drill bit, water is pumped through the nozzle under high pressure to jet the hole ahead of the nozzle. In addition to jetting forward, the nozzle is designed to direct a large portion of the jetting fluid at approximately 45° from horizontal in a reverse direction. The forward jets cut the nozzle advances through the rock and the backward jets balance the reversed forces for better directional control. After reaching the desired depth (i.e., 100 m) from the well bore, the jetting nozzle is slowly pulled back to increase the size of the jetted hole and to clean any formation fines from the lateral. Once retrieved from the lateral and pulled out of the hole, the tubing and attached deflector shoe will be turned from the surface and the process repeated for lateral holes at different angles or depths.

Over the last few years, outstanding economic improvements and successes in stimulating low-permeability marginal reserves by using radial jetting technology have been achieved. It is generally believed that reservoir type (consolidation of sandstone, carbonate, and limestone et al.), vertical/horizontal permeability ratios, and reservoir pressure/temperature play crucial roles in lateral-jet design as well as contributing to the economic success of lateral jet enhancement.

Even with great advances in lateral technology for well production enhancement, no studies have been performed as of yet which track the deployment and direction of laterals as well as the layout pattern of laterals. Such uncertainties have highly restricted the economic justification and further deployment of this technology in stimulating low permeability marginal reserves, which are mainly operated by small producers. It is desirable to develop an array of diagnostic techniques for monitoring the direction and placement of the laterals as well as optimization for the placement of lateral patterns.

4. SENSOR DEVELOPMENT

The general goal for sensor development is to develop a small, battery-powered device able to record accelerations in X, Y and Z directions during or after short-radius lateral drilling, offload the data into a computer, and then to calculate the drilling path after the instrument is returned to the surface. To accomplish this goal, significant technical challenges need to be addressed. The emplaced laterals are less than 50 mm in diameter, and the driving force is delivered via coiled tubing so there is no internal mechanism for having a wired contact with surface equipment.

The drilling system, while under operation, can experience several hundred gravities of force. In addition, to make the turn from the vertical portion of the wellbore to the lateral section, the sensor package has to be short enough to follow the radius of curvature in a specially designed shoe, so that limits the length of the tool to about 40 mm. It was determined that the best measurements of vertical and horizontal deviations would be made by re-entering the lateral after it was emplaced using a modified jet nozzle with only back-facing jets and a self-contained sensor package. Small scale and high *g* piezoelectric sensors can measure deviations quite accurately from a known point. Small, durable batteries were also identified, and a small programmable control chip with on-chip memory is selected to record the data for retrieval at the surface after the tool has been run through the lateral.

General design requirements were constrained in four categories:

1) Function: Measure the acceleration in X, Y and Z directions, and record them into a storage device.
2) Size: All parts (sensor, microcontroller, storage, battery and accessories) must meet the space requirement for fitting into a shell/tube section with dimensions of diameter 13 mm, length 30 mm.
3) Power: Must provide enough power to work for as long as a few hours while the tool is tripped down the well and deployed in the lateral.
4) Environment: Must survive the harsh environments encountered in the lateral: high temperatures, pressures, chemicals, and hydrocarbons.

Based on experience and technologies which are implemented in industrial geology, we can propose our own solution. In this article we took a sample of a small device which is used to monitor the position of a drilling bit during the geological investigation of ground rocks. This device was designed and implemented to be as simple and small as possible by choosing small chip-based accelerometers, a microcontroller, memory chip, and batteries. Figure 1 shows the configuration of the device.

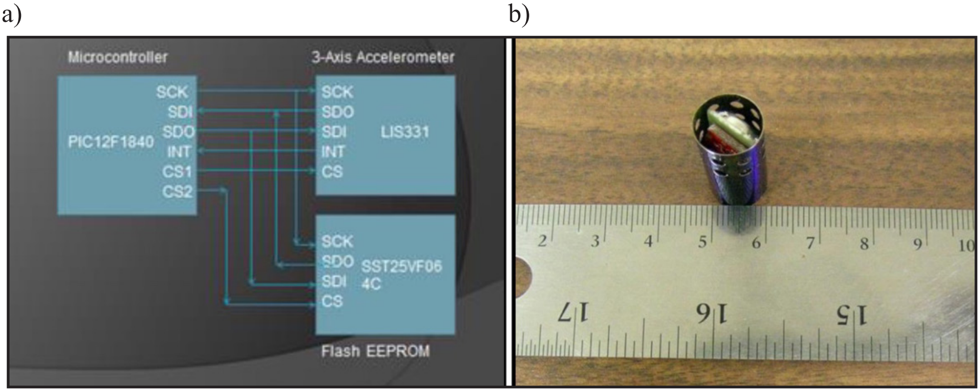

Fig. 1. Device conceptual model: a) basic schematic showing interactions between the microcontroller, accelerometer, and flash memory; b) an implementation in a sized casing

The software configures the device, measures and records the acceleration, and analyzes the recorded data, ultimately computing the path or position by integrating the recorded accelerations twice. The software for the device consists of two parts: control software written into program memory inside the microcontroller; and data processing software, which runs on a workstation or laptop PC to process recorded data and compute the path/position by integrating the recorded accelerations.

5. OPTICAL FIBER SENSORS

In this part, we will try to use all of the advantages of optical fiber sensors to implement them into radial drilling technology for monitoring the lateral direction and placement pattern.

Brillouin distributed strain sensor

Brillouin scattering occurs as a result of an interaction between the propagating optical signal and the thermal acoustic waves in the GHz range present in the silica fiber. Upon the bending, compressing, or heating of a fiber, the Brillouin frequency has shifted with the strain loading.

Conventionally, in the Brillouin strain monitoring system, both Raman and Brillouin scattering are simultaneously detected. The temperature dependence of the anti-Stokes Raman scattered signal allows for a strain-independent measurement. The temperature profile along the sensing fiber is directly obtained by using the ratio of the anti-Stokes Raman power (P_{AS}) to the Rayleigh-backscattering power (P_{BS}), which is dependent on the absolute temperature at a given fiber point according to equation (1).

$$\frac{P_{Bx}(z)}{P_{AS}} = C\left[\exp\left(\frac{h\Delta v_R}{kT(z)}\right) - 1\right]^{-1} \exp(-\Delta\alpha \cdot Z) \tag{1}$$

where C is a constant factor (incorporating the dependence on Rayleigh-backscattering coefficient and Raman gain efficiency effects), h is the Plank constant, k is the Boltzmann constant, T is the absolute temperature and Δv_R is the separation between anti-Stokes Raman and pump light frequencies, and $\Delta\alpha$ is the difference between the fiber loss values at anti-Stokes and pump wavelengths.

In Brillouin scattering detection, fiber stain and temperature variations are inferred from measurements of the Brillouin frequency shift. Changes in the distributed strain (ΔE) at each point z along the fiber can be estimated from the Brillouin frequency shift (Δv_B) , which can be linearly correlated to the strain and temperature as shown in equation (2).

$$\Delta v_B(z) = C_{vB\varepsilon} \cdot \Delta\varepsilon(z) + C_{vBT} \cdot \Delta T(z) \tag{2}$$

where $C_{vB\varepsilon} = 0.048$ MHz$\mu\varepsilon^{-1}$ and $C_{vBT} = 1.07$ MHz°C^{-1} are the strain and temperature coefficients for Brillouin frequency shift. The temperature variation (ΔT) is provided by equation (1), which is based on anti-Stokes Raman measurement.

Tensile and compressive strain measurement

The structural strain measurement of tension and compression can be demonstrated with the Brillouin sensor. Figure 2 schematically shows the experiment measurements of the Brillouin frequency shift. Light from a narrow line width laser is externally modulated, before being amplified by an erbium-doped fiber amplifier (EDFA) and sent via a 3-dB coupler into the test fiber. The returning, backscattered light is then amplified by a second EDFA and is analyzed by a scanning Fabry–Perot (FP) filter and photo detector. The resultant electrical signal is digitized and recorded through a computer station.

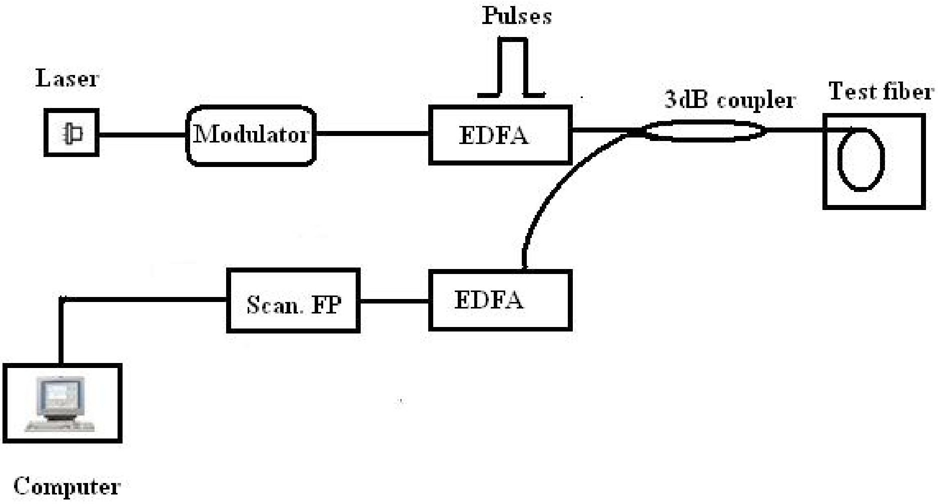

Fig. 2. Schematic diagram of the Brillouin scattering measurements

Engineering design of Brillouin sensor for lateral placement monitoring

To monitor the placement and direction of laterals, strain-sensing fibers must be bonded to the coiled tubing throughout the length of lateral. As shown in Figure 3, the proposed monitoring system integrates four Brillouin distributed strain sensors with 25 mm coiled tubing, in which the strain sensors install around the tubing at the position of 0°, 90°, 180°, and 270°, respectively. The designed monitoring system, with the aid of an additional distributed temperature sensor, will be able to map the vertical and horizontal orientation along the laterals. For example, as an up-bending occurs in a vertical direction, #1 fiber is compressed while the #3 fiber is stretched. Sensors 2 and 4 show no dramatic change in signal. On the other hand, if bending occurs in horizontal, sensors 2 and 4 will change correspondingly.

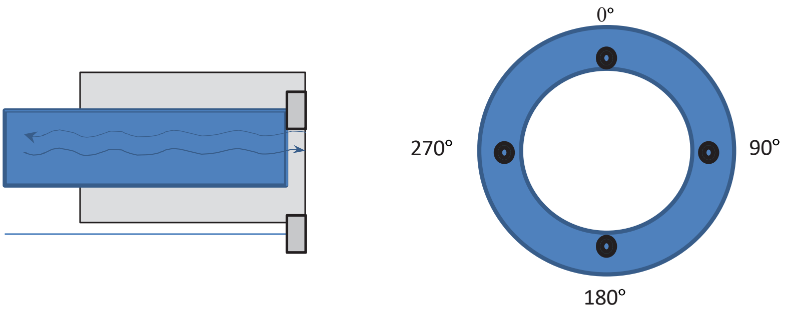

Fig. 3. Sketch of optic fiber sensor placement

The optical fiber will be bonded to a coiled-tubing over the whole length of a horizontal lateral. Glass fiber reinforced thermoplastic tape can be used for bonding the optical fiber and coiled tubing. A bundle of optical fibers, typically polyimide-coated optical fibers, can be bonded to a coiled-tubing in a specific pattern. The bending of the coiled tubing results in corresponding strain changes that will be detected by the Brillouin frequency shift along the horizontal laterals. As a result, the lateral placement can be depicted.

6. CONCLUSIONS

Quite substantial amounts of residual oil (>30%) are left over in low permeability reserves, such as low permeability zones or low permeability reservoirs, when production becomes uneconomical. The key element to enhance production from low-permeability formations is to divert flooding fluids to the un-swept/low-swept formation or to increase the drainage volume by creating connections between a tight formation and the wellbore. This paper show us that we can borrow already used technologies from other areas and implement them into Radial Drilling. We proposed a small and functional enough device which will be able to record (it can record 3-axis gyro and 3-axis acceleration) and show the position of drilling head. Another option is to use fiber optical technology to record the real-time position of drilling equipment.

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