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Interpreting Uncemented Multistage Hydraulic Fracturing Completion Effectiveness Using Fiber-Optic DTS Injection Data

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Summary

Tight-gas, low-permeability reservoirs offer a tremendous challenge with respect to effectively completing and draining a target reservoir. Openhole-packer completions in horizontal wells offer a cost-efficient means of accessing the entire lateral section, assuming the target pay can be effectively stimulated. The challenge with openhole completions compared to more conventional cased, cemented, and limited-entry perforated completions is understanding and controlling hydraulic-fracture geometry; specifically, the number and location of fracture-initiation points and the fracturing-fluid flow into the near-wellbore (NWB) area of the reservoir.

Fiber-optic-based distributed temperature sensing (DTS) offers a method for identifying, quantifying, and evaluating the NWB fracture geometry, the fracturing-fluid distribution in these broad openhole sections, and overall stimulation effectiveness. DTS can also reveal success or issues with respect to effective zonal isolation when using mechanical isolation during the hydraulic-fracturing process.

In this particular case study, a lateral well in a basin-centered gas (BCG) area was completed with swell-packer interval isolation using fracture sleeves for reservoir access. By coupling fracture-treatment responses and openhole log characteristics with the NWB DTS data during pumping and warm-back, an integrated assessment of the completion stimulation effectiveness and efficiency was performed.

The end result of this assessment provided an improved understanding of the current completion performance and allowed optimization of openhole completion projects for future wells in this same area.

Introduction

There is often debate when dealing with North American basins regarding the best approach for completing tight-gas, low-permeability reservoirs. One such debate involves the viability of the openhole packers with fracture sleeves completion method to effectively stimulate long horizontal intervals of a target reservoir. The argument in favor of this completion approach is that a large area between the packers is exposed to the treatment fluid, providing the opportunity to create multiple fracture-initiation points for the fracturing fluid and proppant to enter the target reservoir. This approach also has the advantage of being minimally influenced by NWB fluid friction constraints, such as perforation friction and/or perforation tunnel-induced tortuosity, because the production casing or liner is not cemented. Attempting to verify actual points of fracturing-fluid entry and how many points of entry exist without advanced diagnostics is challenging and cannot effectively be modeled with conventional fracture-modeling approaches.

To better understand the potential NWB fracture complexity in this case study, a fiber-optic-based DTS cable was attached along the outside of the production casing for the entire length of a horizontal well. During the fracturing process, this cable had two primary functions. The first was to monitor fluid travel during fracture stimulation, identifying points of entry into the reservoir and evaluating the effectiveness of hydraulic isolation by the ball seats and the openhole packers between 7 stage intervals along the 900 m horizontal section of the well. The second purpose was to monitor the rate of temperature recovery back toward geothermal reservoir temperature after the stimulation was completed. Based on thermal recovery analysis, crossflow could be identified, points of fluid entry into the reservoir confirmed and an approximation of the amount of treatment fluid into each entry point could be made. Combined, this data helps ascertain where and what sized fractures were most likely created along a single openhole interval.

It is important to note that in this case study, the geomechanical properties of the formation were predisposed to creating or tapping into a natural fracture network and consequently had the potential to create a well-connected stimulated rock volume (SRV), as opposed to discrete planar-type transverse hydraulic-fracture planes. Therefore, a further aim of this particular analysis beyond monitoring the previously mentioned DTS data was to couple that information with hydraulic-fracture treatment data from the stimulations and the fully processed openhole logs. Integration of these analyses resulted in more robust conclusions and recommendations for improving stimulation effectiveness when using this particular completion strategy

Theory and/or Method

DTS System. Fiber-optic-based DTS is a relatively new technique that has been applied to hydraulic-treatment monitoring in recent years (Huckabee 2009). Temperature in the immediate vicinity of the borehole is measured using a customized fiber-optic cable. This temperature profile derived from DTS can be used to monitor fluid movement within the wellbore during hydraulic-fracture treatments and subsequent production. DTS analysis and interpretation is based on comparing temperature changes along the wellbore to infer areas of fluid flow and reservoir entry. Temperature contrast measured in openhole sections during a hydraulic treatment is used to determine where fracturing fluid directly contacts the fiber-optic cable. Recovery to geothermal temperature after the stimulation treatments is also used to infer where and how much stimulation fluid entered the formation. Fiber-optic cables can operate successfully in ambient temperatures up to 300°C for several years and have the capacity to provide a temperature reading every 0.5 m along their length with a response time of a few seconds.

Fig. 1 illustrates the premise of the DTS operating principle. A laser-light pulse is emitted at surface from a DTS interrogator. That light pulse travels at a relatively known speed with a known wavelength. The fiber-optic cable then imparts a backscatter effect to the traveling light as it moves down the fiber cable. This backscatter signal contains anti-Stokes and Stokes Raman components, and this signal is then returned to the same DTS interrogator. The amplitude difference between these two Raman components at a given point provides the capability to acquire temperature information. For this to be effective, the amplitude difference must be calibrated at a point of a known temperature. Once this calibration is complete, the DTS cable will provide accurate temperature along the entire length of the fiber-optic cable.

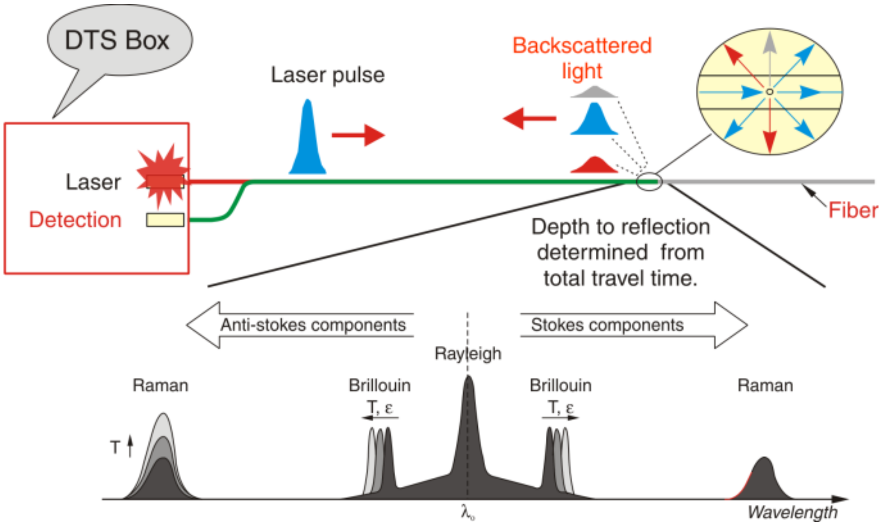

Fig. 1—DTS operating principle; Rayleigh backscatter.

The installation method in which the fiber-optic cable is attached to the casing plays a role in the character of the temperature profiles that are acquired during the stimulation process. In this case study, the fiber-optic cable was deployed and bound to the outside of production casing with clamps along the length of the wellbore. These clamps are typically placed across casing couplings and between casing couplings at the middle of the joint. The point at which these clamps force the fiber-optic cable against the casing provides a good point of thermal conductance to acquire an accurate casing temperature. Because the fiber-optic cable does not continuously contact the casing, there are many gaps where a less-conductive element insulates the DTS cable from the casing; drilling mud, cement, gas, or other materials present in the annular space between the casing and the reservoir might fill this gap. Although it can be small, the gap drastically changes the temperature response in areas between clamps. This installation method creates what appears to be a “noisy” or “spikey” DTS profile along the wellbore during fracture stimulation. However, this noise is not related to the DTS interrogator unit, but is instead related to the installation method.

Examples

DTS Analysis. Two DTS traces are presented in **Fig. 2,** which were acquired during hydraulic-fracture stimulation in an openhole horizontal completion environment. The red and black traces are different traces in time, taken 20 seconds apart. Typically, DTS data is shown in this fashion to display changes in the temperature as the pumping stages progress. The x-axis displays measured depth (MD) in meters (m). The y-axis displays temperature in degrees Celsius (°C). The fluid is moving down the casing from left to right in this image. The fluid passes inside the casing over Interval 3 and enters the annulus and the target formation over Interval 2 through a fracture sleeve in the center of Interval 2. The external casing packers are highlighted to show the different target intervals associated with each stimulation stage. The spikey data highlighted within the dotted circle in Interval 3 is again an artifact characteristic of the fiber-optic cable installation method. These temperatures are in fact accurate and represent the thermal conductance contrast between good and poor fiber-optic cable coupling with the casing.

In **Fig. 2**, Interval 2 is the target interval, and the uniform temperature drop caused by fracturing fluid in the annulus directly contacting the fiber-optic cable can be seen. The character of the cooling response shows that most (more than 70%) of the openhole area was contacted by the treatment fluid, but fluid did not move all the way to either packer. It can be concluded that at least two points of fracture entry existed at 4190 m and 4280 m based on this data. Given the broad interval with temperature response, there was some probability that more fractures could exist within the affected interval, but DTS during stimulation was not capable of determining how many points of fracture initiation exist. That can only be reasonably determined through warm-back analysis immediately after stimulation or subsequent flowback analysis procured throughout the life of the well.

The temperature in Interval 1 (not shown in Fig. 2) located downhole of the injection Interval 2 (highlighted by the solid black circle) was starting to warm back toward geothermal temperature because no new fluid was entering that part of the wellbore. Note that, after pumping Stage 1 and starting the fracture treatment of Interval 2, this region had not completely returned to geothermal temperature because warm back had only been underway for less than one hour. It can take up to a few weeks for tight reservoirs to return to geothermal temperature after stimulating a zone, depending on its geological properties.

During the DTS stimulation-monitoring process in low-permeability sand and shale reservoirs, many of the results and conclusions were based on data provided in a qualitative format (Sierra et al. 2008). It is difficult to provide quantitative analysis with respect to actual injection rates and volumes unless a dedicated thermal tracer is run (Villesca et al. 2011). Because a dedicated thermal tracer was not run in this case study, most of the DTS analysis provided for this project was qualitative in nature.

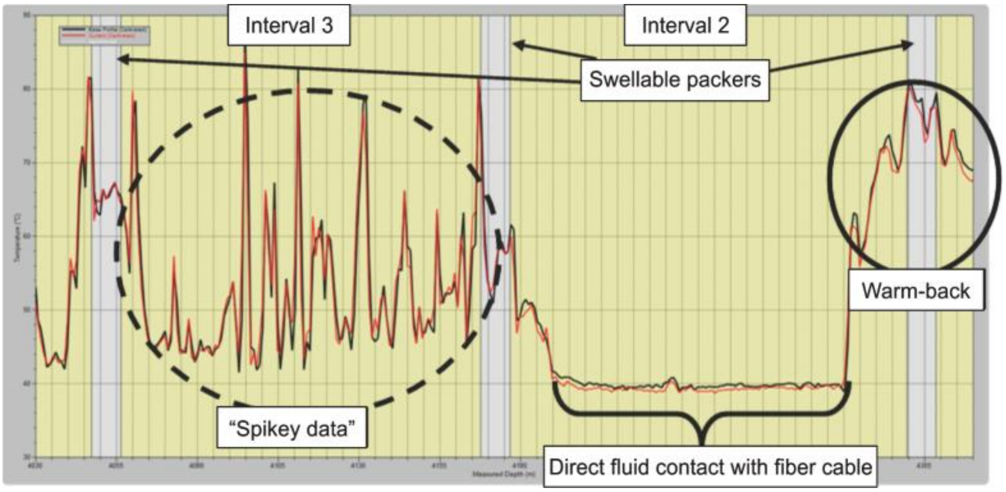

Fig. 2—DTS data acquired during stimulation of the openhole completion Interval 2.

Conclusions

DTS analysis offers key insights into openhole-completion stimulation effectiveness, including NWB fracture complexity (i.e., the number and location of fracture initiation points), qualitative size of the stimulated interval, and an assessment of stage isolation. Secondary insights include an assessment of geomechanical and permeability heterogeneity along the open hole derived from post-fracture crossflow behavior during early shut-in.

The main objective for deploying fiber-optic diagnostics in this well was to obtain a better understanding of the stimulation effectiveness of the openhole-completion system. Coupling the DTS information with the fracture-treatment response and openhole log data helped define completion effectiveness and improve future strategies. Key findings are that multiple points of fracture initiation generally can be created within a broad openhole stage interval, poor isolation can occur because of improper ball-seats or flow around a packer, and such failure compromises stimulation effectiveness in adjacent stages.

Multiple points of fracture initiation and their location are important to the economics of these openhole packer completions. Some hypotheses (Roundtree et al. 2009) suggest that fractures might prefer to initiate at a packer or directly across from the fracture port for openhole completions; however, in this case study, there was little evidence that either occurred. In this case study, there were few stages in which clean long-term temperature-recovery data was available, and identifying points of formation-fluid entry was challenging. The DTS clearly exposed some issues with poor isolation. Leaks through tubing caused by poor ball-seats and the annular leak around a swell packer resulted in warm-back data being obscured for several of the intervals. In this case study, openhole frac treatments with at least three to six points of entry along intervals up to 130 m in length were achieved. The ability to create multiple points of entry seemed largely dependent on whether the interval remained effectively isolated. From the DTS data, it is difficult to quantify the amount of volumes each fracture point has taken during the stimulation treatment. Therefore, caution should be exercised before directly correlating the number of points of entry with production inflow. Using permanently installed fiber-optic cable to perform inflow profiling analyses based on the DTS response under production will help in the future to investigate correlations between fracture-treatment observations and the productivity of the different stage intervals and the fracture-entry points.

The stages where poor isolation occurred because of improper ball-seats or flow around a packer showed on average that more than 50% of treatment intervals remained understimulated. Had these intervals remained well isolated, then perhaps a larger portion of the openhole intervals would have been stimulated. This speaks further to the importance of creating proper zonal isolation in each and every treatment zone. Knowing the extent of completion issues and how they affect the ability to complete the designed fracture treatment can certainly aid in preventing the same issues on subsequent treatment wells.

By incorporating openhole logging data with DTS and treatment data, the operator was able to further develop an understanding of fracture initiation and evaluate fracture placement within a given interval. The logging data also helped identify the driving mechanisms for crossflow. In most cases, the crossflow took place in an area with higher shale volume and formation stress, as calculated in the processed log. Crossflow also seemed to take place in areas with the lowest permeability relative to the other points of fluid entry within a given treatment interval. Although crossflow showed fluid movement during shut-in, it did not indicate creation of significant fracture entry points.

Long-term thermal-recovery response in the openhole intervals after the fracture treatments were completed helped identify that the sandy portions of the openhole treatment interval likely received the largest volume of treatment fluid, while the portion of the openhole intervals with higher shale volumes seemed to receive less treatment volume. Using this information, the most dominant fractures created within an individual interval were identified and could be used for more representative dynamic reservoir-performance modeling in the future.

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