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Multistage Hydrofracturing Efficiency Analysis and Horizontal Well Inflow Profiling Using Spectral Noise Logging Technique

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Abstract

One of the most cost-effective technologies used during the development of hard-to-recover reserves is horizontal drilling with multistage hydraulic fracturing. This paper is dedicated to the assessment of multistage hydraulic fracturing effectiveness in formations with low-permeability and high clay content.

The paper demonstrates how the integrated logging suite supplemented with High-Definition Spectral Noise Logging tool can provide valuable information on the flowing reservoir zones behind the liner and therefore the multistage hydraulic fracturing effectiveness.

Based on the results of logging survey carried out in flowing regime with nitrogen being injected into the well, the hydraulic fracturing job performance was assessed and the inflow intervals were identified. As a result of the multistage hydraulic fracturing job, incremental oil production was achieved. On the basis of an integrated logging survey and field data analysis, the integrity of well completion elements was also checked.

Introduction

Hydraulic fracturing is the most efficient type of well interventions to ensure incremental production of hydrocarbons. In the regional petroleum industry hydraulic fracturing started to be put into practice since the middle of the XXth century but later on the interest in hydraulic fracturing was practically entirely lost after the highly productive Western Siberia fields had been brought into development. As the share of oil deposits in low permeability reservoirs in the structure of reserves was growing, the interest in hydraulic fracturing was revived in the early 90s. This technique is being constantly improved and upgraded in accordance with the new objectives and conditions. An increased number of hydraulic fracturing stages during development of low permeability reservoirs leads to an increased number of fractures penetrating the oil reservoir and therefore to a larger drainage zone. Identification of flows through induced fractures in the target reservoir is one of the criteria for assessing a hydraulic fracturing job effectiveness. The situation becomes even more complicated when the well is equipped with an uncemented liner. In this case the reservoir flow zones and hydraulic fracturing sleeves flow zones may differ considerably.

The High-Definition Spectral Noise Logging hardware and software system has been developed to solve such tasks as location of flowing hydraulic fracturing sleeves, identification of behind-casing flows and estimation of their rates, and integrity assessment of swell packers. The flowing zones in the reservoir, behind the liner, were identified by the SNL high-frequency component. This paper describes a new technique of defining an inflow flow profile inside the wellbore based on the SNL data. A technique that uses the low-frequency noise power for estimation of inflows inside the liner was applied for the first time ever.

Technologies

Spectral Noise Logging

The Spectral Noise Logging suite is a hardware and software system developed for recording acoustic signals generated in the wellbore in a wide frequency range [1-4]. The key component of the system is the High-Definition Spectral Noise Logging tool. The highly sensitive hydrophone which is part of the SNL-HD tool can record sound pressure levels starting from 1 mPa (threshold sensitivity) and has a wide dynamic range (100 dB). The SNL-HD is equipped with special metrological equipment to monitor the technical characteristics and sensitivity of the measuring instruments while manufacturing and before logging operations. A special calibration stand was developed for estimation of amplitude and frequency response of the SNL-HD tool with accuracy up to 3 dB. There is also a mobile calibration tester available to test the tool sensitivity in field conditions immediately before and after the logging survey in the frequency band up to 60 kHz. This measuring system not only assures a high quality of the data recorded by the tool but also their uniformity. This applies to the test measurements performed both in lab conditions and in the wellbore.

The software system for SNL data processing and visualisation is equipped with advanced adaptive filters and digital data processing equipment. The software performs automatic data matching and data quality control, calculates spectral panels and adaptively adjusts their amplitude, filters out statistically significant signals, and automatically recognises the signal.

Acoustic Flowmeter. When an injector or a producer is logged in injection of flowing regime, acoustic signals generated by fluid flow in the wellbore can very often be observed. However, not any fluid flow in the pipe can be the source of acoustic waves but only a turbulent flow. A turbulent flow is formed when the fluid velocity across the pipe section reaches a critical value determined by the Reynold's number. The pipe cross-section should be estimated in this case after deducting the area occupied by the toolstring in the wellbore.

The theory of sound generation by turbulent flow was originally suggested in early 50s in M. Lighthill's works (5) where he proposes a solution of heterogeneous wave equation deduced on the basis of equations of continuity and momentum conservation, with turbulent flow moving in infinite space. In late 50s N. Curl [6] supplemented Lighthill's theory by adding rigid boundaries to the turbulent flow (in our case these are pipe walls). According to the Lighthill - Curle's heterogeneous wave equation, the acoustic power depends in a complex way on the pipe and fluid flow parameters:

$$W \sim \frac{\rho u^8 d^2}{a^5}, \tag{1}$$

where W is acoustic power, u - flow velocity, ρ - average fluid density in the pipe cross-section, a – sound velocity in fluid and d - pipe diameter which determines the typical turbulence scale.

Such strong dependence of the generated acoustic signal power on flow velocity along the wellbore makes SNL very sensitive to any variation of flow velocity in the pipe and wellbore, and makes it possible to use the SNL tool as a sort of acoustic flowmeter. Currently, this technique can yield unambiguous results only in case of a single-phase flow, as a consequence of sound velocity and density depending heavily on the fluid type. The resulting injection/flow profile is relative and should be calibrated to the total injection/

flow rate measured at surface. This technique was proved by multiple lab experiments with gaseous and liquid fluids, during which the wellbore flow velocity profile derived according to SNL data was found to be in good correlation with the spinner data. The accuracy of calculations made according to the acoustic flowmeter technique is about 3%.

Daisy Chain. To eliminate the acoustic signals produced by SNL-HD and other tools in the toolstring as they move along the wellbore, the Spectral Noise Logging is recommended to be performed at stations. It is especially important that the measurements are taken at stations in case of low-power acoustic signals generated, for example, by fluid flow at relatively low underbalance or overbalance pressures. Low-power acoustic signals are also generated by fluid flows through well completion leaks at low fluid flow velocities. When logging at stations, the SNL data quality depends primarily on the duration of stationary measurements and the depth step. The depth step is selected according to the survey objectives and the logging interval. In some cases, for example, for the purpose of leak detection, the distance between stations can be increased up to 3 m (10 ft). In order to reduce logging time in long horizontal wells, the measurements may also be taken at 3 m intervals. To increase logging speed during SNL surveys which in the majority of cases are performed at stations, Daisy Chain technique is applied. This logging technique requires the simultaneous use of several tools in one toolstring and a special data merging algorithm. In this case, the interval covered by logging tools at each station will be several times larger. Accordingly, the number of stations can be reduced several times without compromising the depth resolution, which can considerably cut down the logging time. The distance between stations depends on the number of SNL-HD sensors in the Daisy Chain toolstring. The SNL-HD toolstring is shown below in Fig. 1.

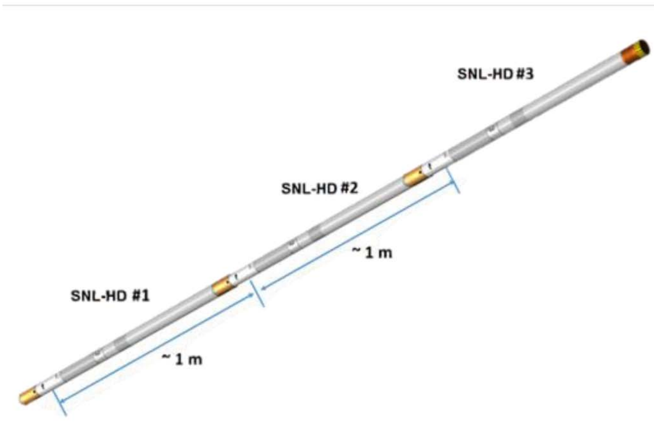

Figure 1—Daisy Chain toolstring with three SNL-HD sensors

Temperature Modelling

Temperature modelling is an effective tool for defining quantitative distribution of fluid inflows from reservoir (inflow profile). The temperature logging technique is based on the analysis of temperature anomalies generated in the reservoir both during production and after a hydraulic fracturing. The most informative temperature logs in terms of quantitative assessment of reservoir parameters can be recorded in a well that has been steadily flowing for a long period of time.

TermoSim™ software package is used for numerical modelling of temperature and hydrodynamic patterns in the well-reservoir system with the purpose of flow profiling [7-9].

The TermoSim™ software package can simulate in detail the thermodynamic processes taking place in the well and the near-wellbore zone. The accuracy of the results totally depends on the completeness and quality of input parameters which include the information about porosity and permeability of the target formation and surrounding rocks, and insulation properties that are determined mostly by the well completion design. The reservoir flow zones are specified on the basis of SNL data and the results of a qualitative analysis of anomalies on HPT logs recorded in different well operation regimes. The type of fluid is specified on the basis of multiphase sensor data analysis.

Field overview and reservoir parameters within the survey zone

Lithostratigraphic characteristics of the formation

The field under study was discovered in 1978 in the West Siberian Basin and classified as the gas-condensate type. The development target is a lithologically screened reservoir occurring at a depth of 2800-2850 m. The average formation water salinity is 16 g/l and specific electrical resistivity 0.14 Ohm·m. The average reservoir permeability varies from well to well in a narrow range of 0.9 – 18.4 mD. The reservoir consists of grey sandstones, often silty, micaceous, with argillaceous or argillaceous/carbonaceous cement. The reservoir fluid is exposed to high pressures (up to 28 MPa) and temperatures (up to 98°C). The dew point varies from 16 to 18 MPa.

Case study

This paper provides a case study of production profiling using acoustic flowmeter and temperature modelling techniques after a multistage hydraulic fracturing job to monitor its effectiveness.

The surveyed horizontal well was completed with uncemented liner and a system of casing packers and hydraulic fracturing sleeves. The entire volume of water injected during the hydraulic fracturing was recovered back a few days later. The production water cut after putting the well on stream was 50%. After three months of production the water cut increased to 70%.

At the preparatory stage, before commencement of the hydraulic fracturing job, more than 550 m^3 of water was pumped into the well, which resulted in the well flowing mainly water during the survey. The fluid flow rate was 75 m^3/day.

To profile the flows from reservoir into horizontal wellbore through hydraulic fracturing sleeves, and assess the integrity of sleeves and casing packers, an integrated logging suite containing a standard set of sensors: GR, CCL, HPT, pressure gauge, PLT, HEX, multiphase sensors, and SNL-HD of the Daisy Chain modification was run. The integrated logging survey was conducted several months after the multistage hydraulic fracturing job.

The survey was performed in several consecutive regimes. The logging programme was designed so as the baseline log could be recorded under shut-in conditions. For this purpose, the well remained shut in for 11 days before the survey. The logging toolstring was run on coil tubing. Then nitrogen was injected into the annulus to stimulate the flow. The nitrogen was injected for more than 24 hours to stabilise reservoir temperature and pressure. After logging in the steady flowing regime, the well was shut in and logging was continued under transient conditions: 1 hour and then 12 hours after shut-in. The integrated logging suite schematic is shown in Fig 2.

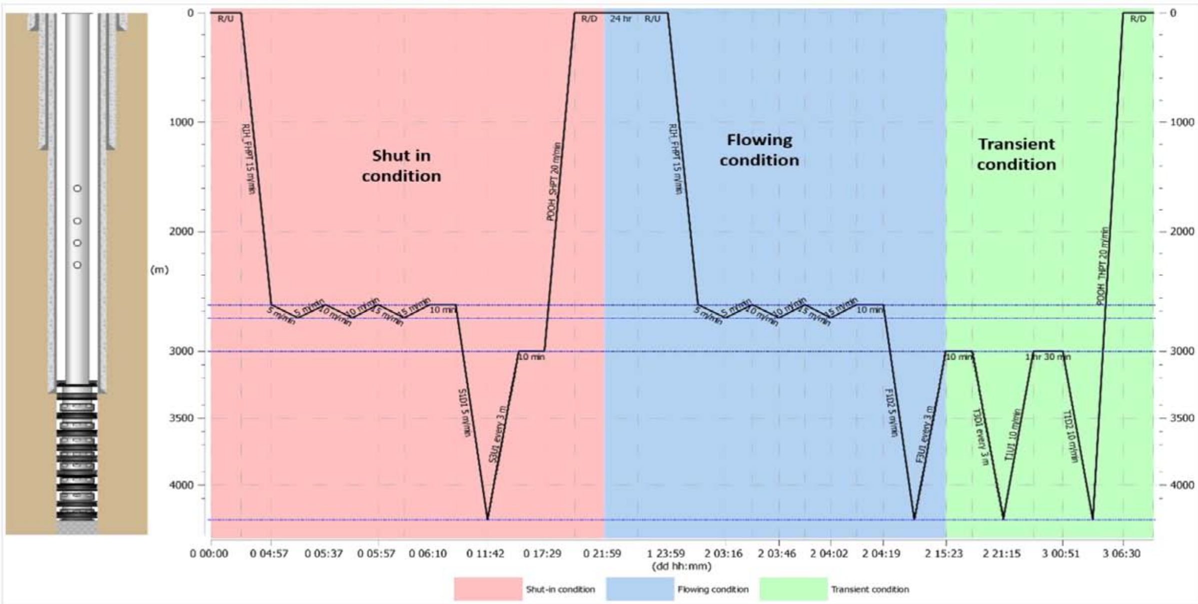

Figure 2—Schematic of the integrated logging suite including SNL-HD technique

To shorten the logging time in 880 m long horizontal wellbore section without reducing the SNL data resolution, the survey was run according to the Daisy Chain procedure. The SNL was performed at stations in order to minimise the interference associated with the tool motion. The distance between stations in the surveyed well was 3 m, which was equivalent to the continuous logging speed circa 3 m/min.

Inflow profiling in horizontal wellbore section

The main integrated logging results are shown in Fig. 3.

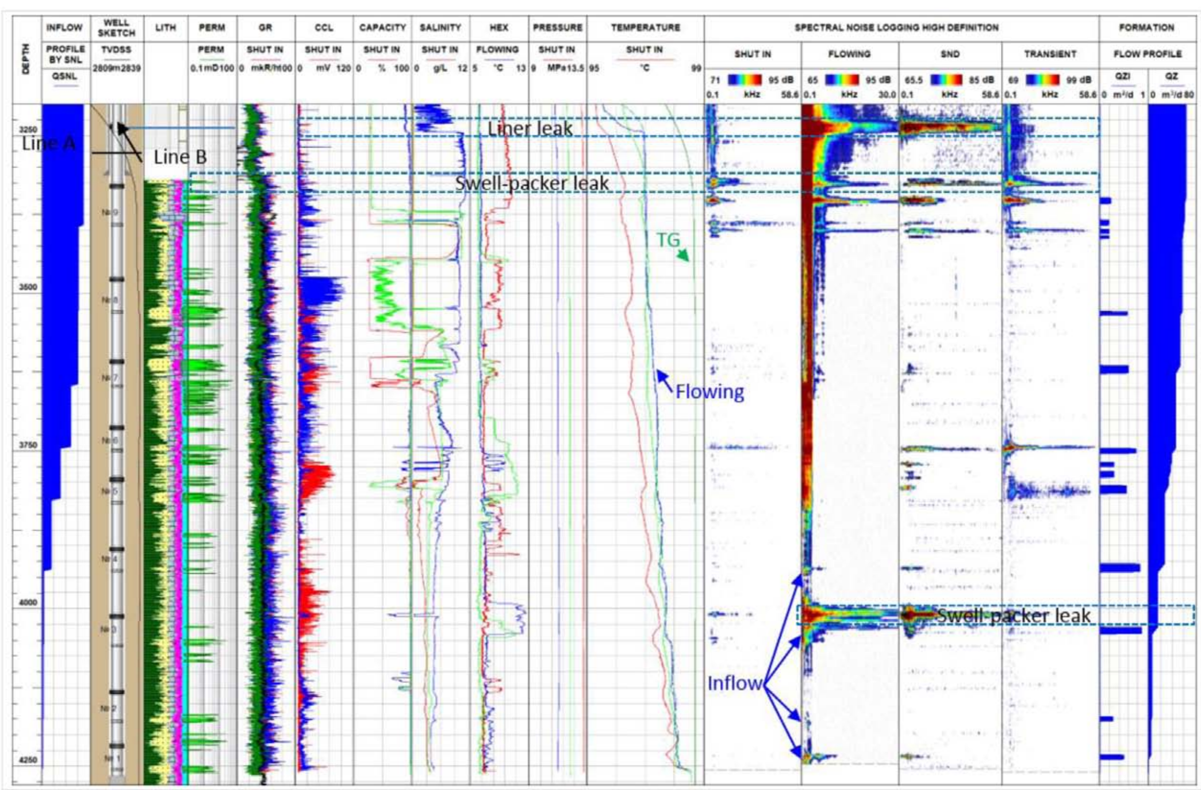

Figure 3—Results of the integrated logging suite including SNL-HD technique

The active flow zones were identified according to the SNL data (See SNL panel). Fluid flows along the active reservoir zones, including the flows through fractures created by multistage hydraulic fracturing, generate depth-specific acoustic signals that occur in a particular frequency spectrum extending to the high-frequency range.

Inflow profiling in horizontal wellbore section using Acoustic Flowmeter. Inflow profile through hydraulic fracturing sleeves was determined with the Acoustic Flowmeter, based on the analysis of SNL-HD low-frequency component. According to the multiphase sensor data (capacitance and salinity) the inflow contained mainly water and it can be therefore assumed that the relationship between fluid density and sonic wave velocity in fluid remained more or less constant. As the liner diameter was the same (4½ ″) in the entire horizontal wellbore section, all acoustic signal power variations were caused by the changes in flow velocity in the horizontal wellbore section.

To estimate the acoustic signal power of the low-frequency component of the spectrum, a frequency range below 10 kHz was selected because the most intensive acoustic signals from the wellbore flows had been observed in this well in this particular frequency range. Although the flow rate of the fluid produced from the entire horizontal wellbore section was only 75 m^3/day, the linear velocity of the flow along the liner was sufficiently high to create a turbulent flow. This turbulent flow along the wellbore generates low-frequency acoustic signal of the intensity varying with flow velocity increase.

The SNL column in Fig. 3 contains a curve representing the relative flow velocity in the horizontal wellbore section estimated according to the SNL data. To improve the accuracy of flow velocity estimations, the sound produced by the tool itself was taken into account, and, in particular, the sound generated by the tool electronics, which was observed even when there were no other acoustic signal sources in the well. The relative profile of flow velocity in the intervals between hydraulic fracturing sleeves was averaged, disregarding the intervals where acoustic signals from flowing reservoir zones and fractures were present together with the low-frequency range signal. At the depth shown by Line A the value of fluid flow velocity should correspond to the fluid production rate in the horizontal wellbore section and therefore this interval was selected for the general profile normalisation and estimation of absolute values for the inflow profile in the horizontal wellbore section.

It should be noted that above the depth marked as Line B the pipe ID varies because the liner changes over to the tubing of a smaller diameter (3½ ″), resulting in an increase of low-frequency acoustic signal power at this depth. No flow velocity variations take place at this depth.

The inflows through the hydraulic fracturing sleeves show that the main fluid (water with traces of hydrocarbons) flows are from the reservoir zones across hydraulic fracturing stages 4 through 7 where, according to the open-hole data, the most extensive and permeable intervals of the multilayer reservoir occur, with one fifth of the total well production (12 m^3/day) coming from sleeve 6. The zone with such low flow rate could not be located by the spinner but HEX sensor (See HEX column), which has a lower sensitivity threshold, showed a slight variation in the readings. A small volume of fluid enters the wellbore through the top hydraulic fracturing sleeve 9. The reservoir interval across the lower three sleeves contributes only slightly to the well production, which is partially due to poor reservoir quality in this zone.

Temperature modelling-based inflow profile. Temperature simulations help to estimate inflow profiles in horizontal wells including inflows both from sleeves and directly from the reservoir. It can be seen that the flowing temperature curve (blue line in the HPT column) contains anomalies at each sleeve and between them, which is due to the flows from the reservoir.

In this particular case a quantitative analysis of the temperature curves is complicated by the fact that a large volume (500 m3) of cold water was injected into the well immediately before the survey, resulting in an uncontrollable temperature drop in the near-wellbore zone. The geothermal profile (green TG line in the HPT column) that was reconstructed on the basis of temperature data recorded near the rathole indicates that all curves show a temperature decrease in comparison with the initial temperature. The estimation of inflows from the reservoir is also adversely affected by the fact that the reservoir flows are disguised by wellbore flows. Despite of all these drawbacks, an inflow profile was successfully estimated by simulating all temperature logs at the same time and with the same set of input parameters: permeability, reservoir pressure, and skin factors (see Inflow Profile column in Fig. 3). It can be seen that the profile generally correlates with the one derived with the assistance of the Acoustic Flowmeter. However, besides inflows from the sleeves, there are also some flow zones where the fluid is coming directly from the reservoir. Such flow zones correlate well with acoustic signals and permeable intervals identified according to open-hole data (See Fig. 3 and 4).

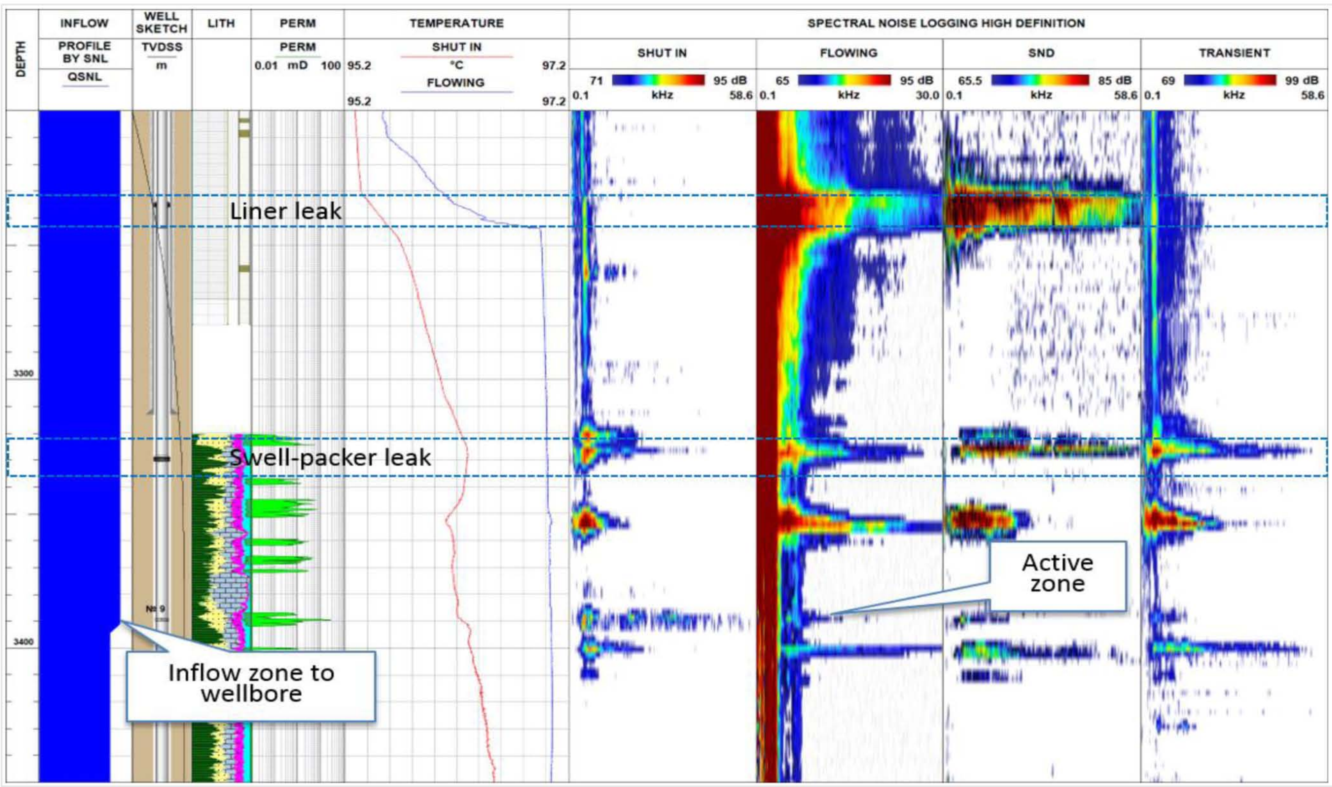

Figure 4—Zoomed-in view of leaks in the completion string and packer 9 - HPT, SNL-HD

Wellbore cross-flow during shut-in. Additional information was obtained by analysing a temperature log recorded during a long shut-in, where some cooling anomalies were detected near the hydraulic fracturing sleeves due to the cold water injected before the survey. The SNL-HD data also indicate occurrence of typical high-frequency signals at the depth where hydraulic fracturing sleeves are installed. Based on the combined analysis of shut-in SNL-HD and HPT data recorded in the horizontal wellbore section, a conclusion was made that a small wellbore cross-flow takes place in the interval between hydraulic fracturing sleeves 3 and 9. This suggests that formation pressures in different parts of the horizontal wellbore section are different. The weighted average formation pressure in the well during the 11 days shut-in period was 13.4 MPa, which is 28 MPa lower than the initial reservoir pressure.

Horizontal wellbore section integrity survey

After the multistage hydraulic fracturing job, and integrated logging survey was run in the well to check the integrity of swell packers and well completion elements. The SNL-HD tool identified leaks in the liner and casing packers 3 and 9 under the logging conditions (zoomed-in view of leaks in the liner and packer 9 is shown in Fig. 4). The SNL-HD data also indicate that the low-frequency acoustic signals captured in flowing regime during nitrogen injection confirm that a cross-flow takes place from the overlying unperforated reservoir zones (Fig. 3) due to a leak in packer 9.

Conclusions

This paper describes the method of multistage fracturing effectiveness assessment using an integrated downhole suite. Combined application of SNL-HD and HPT tools and subsequent temperature simulation has made it possible to assess flows from the fractures created during the multistage hydraulic fracturing in the horizontal well and check well completion integrity and swell packer operation. Upon an analysis of the logging data, fluid flow zones were identified in the reservoir and quantitative estimation of inflows from each reservoir zone associated with hydraulic fracturing stages was carried out.

To estimate the profile of fluid flows into the wellbore through hydraulic fracturing sleeves, Acoustic Flowmeter technique was applied. Although this technique has started to be used for flow assessment instead of the conventional PLT only recently, it has already positioned itself confidently in the well services market, especially in horizontal well logging where the presence of mechanical parts in the logging tools cause additional difficulties during the survey. This technique relies on the fact that the low-frequency acoustic signal intensity depends on the wellbore flow velocity, which affords an opportunity to estimate relative inflows from each hydraulic fracturing sleeves.

The profiles of inflows through hydraulic fracturing sleeves plotted according to the Acoustic Flowmeter data and the profile of inflows from reservoir into wellbore according to temperature modelling are in good correlation with each other. The difference has been interpreted to be due to flow contribution from the reservoir zone behind the liner. The highest flow rates were identified in the middle part of the horizontal section. These inflows are associated with hydraulic fracturing stages 4 through 7 due to better reservoir properties in this interval of the target multilayer reservoir. In general, the integrated downhole survey results have confirmed that the hydraulic fracturing job was successful.

Acknowledgements

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List of Acronyms

CCL,	Casing-Collar log
GR	Gamma Ray
HEX	Heat Exchange Sensor
HPT	High Precision Temperature
SNL	Spectral Noise Logging
SNL-HD	High-Definition Spectral Noise Logging

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