Formation flow rate control method in multi-layer production

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Abstract: The article describes a method of flow rate control of separate formations in multi-layer production by noises frequency response (FR). The noise FR is converted into electrical signals scaled in proportion to the flow rates using secondary facilities. The pump noise is suggested to be reduced with the quarter-wave acoustic resonator working as an acoustic filter.

1. Introduction
To control oil production from separate formations, the following instrumentation is used: flow meters, pressure gauges, thermometers [1-5].

The disadvantage of this method is that tubes, packers, downhole cameras, regulating choke restricting devices, measuring instruments, conductive cables, disconnectors, telescopic joints and other equipment are run into the hole. As a result, because of this set of equipment, the well flow rate measurement unit has low reliability and control efficiency.

2. Research
A more reliable method is frequency response (FR) measurement of noise generated by turbulent oil flows through perforations with further conversion into electrical signals proportional to formation flow rate [6].

Because the geometry of the perforations may not be identical, so the noise frequency response will also differ. This is similar to unique fingerprints of people. A change in formation flow rate causes a change in the noise frequency response.

For each oil formation, there is perfomed a measurement of amplitude-frequency spectra of the noises generated by every formation, turbulent vortexes of oil-water-gas mixtures coming from the perforations in a production well. Noise amplitude-frequency spectra measurement is implemented with recording instruments, including a hydrophone (run on a cable into a hole to the level of an oil formation), a frequency meter and an electronic unit for the information processing (installed at the wellhead).

Next, a program for the electronic unit is developed enabling processing of information about the flow rates according to the amplitude-frequency spectra of the noises generated by a separate oil formation. This method allows a concurrent flow rate control in multi-layer oil production using a single lift.
It should be noted that the accuracy of flow rate control by means of frequency spectra is affected by a pump noise. To reduce the impact of the pump noise, it is necessary to suppress it by means of quarter-wave resonators, i.e., acoustic filters.

An acoustic filter is an acoustic resonator made in the form of a vessel communicating with the external environment through a small hole or tube. Its characteristic feature is an ability to perform low-frequency self-oscillation, with wavelength much greater than the size of the resonator. According to Helmholtz and Rayleigh theory, an acoustic resonator is regarded as an oscillation system with one degree of freedom.

The kinetic energy is considered to be concentrated in a layer, moving in the tube, called the throat of an acoustic resonator, like a hard rod; and the potential energy is associated with elastic deformation of the medium contained in the volume.

The acoustic resonator natural frequency does not depend on the shape of the vessel and the pipe cross section and is expressed by the formula [7]:

$$f = \frac{c}{2\pi \times (F/Vh)^{1/2}},$$

where:
- $c$ is the speed of sound in the medium (drilling mud), m/s;
- $V$ is the resonator volume, m$^3$;
- $F$ and $h$ are the cross-sectional area, m$^2$, and the tube length, m, respectively.

This property of an acoustic quarter-wave resonator, i.e. reflection and absorption of energy at a given frequency from the sound vibration spectrum can be used, first, to reduce noises if their frequency is in the information signal frequency range, thereby to increase the signal/noise ratio; for instance using an acoustic resonator for absorbing the noises created by electrical submersible pumps (ESPs).

Knowing the pump noise frequency, which is to be measured at the stand of the manufacturer, it is possible to determine the size of an acoustic quarter-wave resonator.

The property of a quarter-wave acoustic resonator to suppress low-frequency noises and convert them into ultrasound is implemented in papers [8-11].

Quarter-wave acoustic resonators are placed in the tubing body above an electric submersible pump (ESP). This arrangement allows the resonators to suppress the pump noise.

In Fig. 1 there is a diagram of a production oil well, with a hydrophone and a quarter wave resonator in the tubing above the ESP.

From figure 1 it can be concluded that the ESP operation in a well is accompanied by the noises of productive formations and the very ESP. In case of marginal wells, occasional pumping is possible, i.e., the ESP will be periodically switched off and, accordingly, noise $S_{12}(f)$ will disappear for this period. At the same time, noises $S_{14}(f)$ and $S_{15}(f)$ will propagate in the well, creating the effect of well operation, i.e. in the absence of flow, the secondary equipment will register the flow. To prevent this phenomenon, it is proposed to use an acoustic quarter-wave resonator, designed to suppress the ESP noise to provide an accurate control of flow rates, and to create start and stop commands for the flow rate control. During the ESP operation there is an acoustic mark in the form of the frequency absorbed by an acoustic quarter-wave resonator; this mark will serve as a start signal for the secondary equipment to control the flow rate. When the ESP is switched off, in the noise spectrum there will be an acoustic mark in the form of the frequency recovered by an acoustic quarter-wave resonator, which will serve as a stop signal for the secondary equipment to control the flow rate.

The second variant to start and stop the flow-rate control can be the ESP operation control signals. The on/off control signals for the ESP may serve as on/off control signals for the flow rate control by the secondary equipment.
Figure 1. Production oil well diagram.

1 – oil formation P1; 2 – oil formation P2; 3 – oil-water-gas mixture; 4 – ESP; 5 – quarter-wave resonators; 6 – tubing; 7 – dynamic level; 8 – gas; 9 – casing; 10 – lubricator with a hydrophone; 11 – hydrophone; 12 – noise S_{18}(f) propagating in the tubing and making a sum of noise S_{6}(f) and S_{17}(f); 13 – noise transition from the well into the liquid filling the tubing; 14 – noise S_{13}(f) propagating in the production well and consisting of four amplitude-frequency spectra of noises: noise S_{14}(f) is proportional to the formation P1 oil-water-gas mixture flow rate, noise S_{15}(f) is proportional to the P2 oil-water-gas mixture flow rate, noise S_{11}(f) generated into the well from the tubing and noise S_{12}(f) generated by the ESP with quarter-wave resonators above the ESP; 15 – noise S_{16}(f) propagating in the production well and comprising two amplitude-frequency spectra of noises S_{14}(f) and S_{15}(f); 16 – oil-water-gas mixture turbulent flows with varying characteristics when P2 oil formation flow rate varies; 17 – oil-water-gas mixture turbulent flows with varying characteristics when P1 oil formation flow rate varies

Figure 2 shows the amplitude-frequency spectra of noises S_{13}(f) and S_{14}(f) propagating from two oil formations to the recording instruments. There is an additional ESP noise source on the propagation path.
Figure 2. Amplitude-frequency spectra of noises $S_{13}(f)$ and $S_{14}(f)$ propagating from two oil formations: a) shows the frequency spectrum of noise $S_{1d}(f)$ generated by perforations of oil formation P1; b) frequency spectrum of noise $S_{1e}(f)$ generated by perforations of oil formation P2; c) frequency spectrum of noise $S_{1f}(f)$ propagating in the well and consisting of two frequency spectra of noises $S_{1d}(f)$ and $S_{1e}(f)$; d) the total frequency spectrum of noise $S_{14}(f)$, consisting of noises $S_{1d}(f)$ and $S_{1e}(f)$ generated by perforations of oil formations P1 and P2, with the noise in the form of noise $S_{1f}(f)$ generated by tubing and ESP; e) the total frequency spectrum of noise $S_{15}(f)$, consisting of noises $S_{12}(f)$ and $S_{17}(f)$, which in turn consist of noises $S_{11}(f)$, $S_{12}(f)$, $S_{14}(f)$, and $S_{15}(f)$; f) frequency spectrum of noise $S_{19}(f)$, received by the hydrophone and filtered by the recording instrument (frequency spectra of noises $S_{1d}(f)$ and $S_{1e}(f)$ of the waves are proportional to the flow rates of the respective formations, with an appropriate calibration).
Amplitude-frequency spectra of noises $S_{13}(f)$ and $S_{14}(f)$ propagating from oil formations associated with fluid flow heterogeneities and elastic oscillations of the walls of the channel, in which the flow moves. Heterogeneities of the filtration flow occur due to vortex formation on the rough walls of the reservoir rock capillaries. The hydrodynamic noise acoustic properties for these conditions are also related to the channels configuration and walls apart from the flow heterogeneities velocity and structure.

The noise amplitude-frequency spectra are also affected by additional flows that are associated with fluid motion in perforations $S_{15}(f)$ and damaged tubes at the annulus in cross-flows and in cracks in the cement stone and cavities. Acoustic noises in the well for these additional situations have intermediate characteristics between the radiation parameters of turbulent flows in pipes and filtration flows in reservoirs.

The given experimental studies form a basis for a method of downhole spectral noise logging [12]. Based on the experimental studies of hydrodynamic sound formation in the well, a flow noise spectrum can be divided into three frequency bands. Fluid flow in pipes (casing, tubing) generates noise in the frequency band up to 100 Hz. With the flow in cavernous and fissured environments, the noise spectrum has maximum in the range of 100 to 2000 Hz. The filtration flow noise spectrum in reservoirs is in the band of 2 to 20 kHz.

The noise in the form of ESP noise $S_{13}(f)$ consists of mechanical, electromagnetic and even aerodynamic noises and vibrations, which are closely related to each other.

3. Conclusion

The role of acoustic methods of study, control and diagnostics are well known. These methods allow one to obtain huge amounts of information about the state of materials and structures that are difficult to perform with sensors.

Acoustics also provides wide opportunities for study of the properties of materials, substances, and structures.

The method of well layers flow rate control in multilayer production under study is practically analogous to spectral noise logging. In general case, the spectral noise logging is aimed at determining the technical condition of wells and their operational parameters.

The method of flow rate control of separate formations in multi-layer production by formation noise frequency response (FR) is a promising energy-saving technology, which allows one to determine the flow rate of several productive formations in oil wells and thereby to cut the costs of oil companies without major capital investment. Using this method, it is possible to determine the efficient formation zones, as well as to determine the optimal modes of wells operation that will increase the efficiency of production.

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