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Laboratory and field observations of stress-wave induced changes in oil flow behavior

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Summary

We present recent results of laboratory and field experiments designed to validate and quantify the phenomenon of seismically enhanced oil production in marginal reservoirs. Controlled laboratory experiments were performed where mechanical stress oscillations at 100 Hz or less were applied to sandstone cores while flowing oil and/or brine at constant flow rates. Steady-state flow and simulated flooding experiments indicated that stress stimulation causes significant changes in the ability of one fluid to displace the other and on the preference that the rock has for trapping one fluid over the other. For Berea sandstone, which is highly water wet, stress stimulation caused oil production to be impeded during water floods and caused the bulk fluid pressure drop across the core to increase during steady-state simultaneous flow of oil and brine. A possible explanation of these observations is that stimulation caused the core to become more oil wet.

Field stimulation tests on producing reservoirs at Lost Hills, California were performed using a downhole fluid pressure pulsation device. Stimulation was applied in one well for 50 days total during July - November 2000. Two groups of producing wells were monitored for changes in oil cut and oil production during the test. A control group of 26 wells displayed an oil-cut increase of 29% and an oil production increase of 26% which are clearly correlated with the stimulation treatment. A larger group of 60 wells showed 11% oil-cut and 17% production increases. Similar increases were observed during the October 1999 Hector Mine earthquake, magnitude 7.1, in the Mojave Desert about 230 miles from Lost Hills. Downhole seismic monitoring of the stimulation wavefield is being used to help quantify the frequency range and energy threshold required for effective production enhancement.

Introduction

Roughly 60% of domestic oil resources remains unproduced, partially due to limitations in existing EOR methods. Anecdotal production data, as well as historic field and laboratory experiments performed by Russian and U.S. researchers, have shown that seismic (stress) wave stimulation can enhance oil mobility and total recovery in mature reservoirs (Beresnev & Johnson, 1994). Low-amplitude seismic waves in the frequency range of roughly 10-500 Hz can directly increase oil mobility over large distances. Previous field tests with different seismic sources have yielded mixed or inconclusive results for enhancing oil production. In some cases seismic stimulation increased production rates by 50% or more, but in other cases production was unchanged or actually declined. This is due primarily to the fact that existing laboratory and field experimental data are not comprehensive enough to allow prediction of the physical conditions under which stress-wave stimulation is most effective.

Recent laboratory and field research is beginning to provide the experimental data needed to identify physical mechanisms which govern the seismic stimulation phenomenon (Nikolaevski et al., 1996; Roberts & Sharma, 1999; Roberts et al., 2001). The new results presented here are compelling because they were obtained under controlled experimental conditions and show a clear correlation between applied stress waves and fluid production behavior. As more data are collected for a wider range of physical conditions and downhole source technologies, stress-wave stimulation should eventually become one of the more valuable and predictable enhanced recovery tools available to the oil and gas industry.

Laboratory Experiments and Results

A specialized laboratory core flow apparatus, shown schematically in Figure 1., was assembled to study the effects of low frequency stress oscillations on fluid flow behavior in rock core samples. The main component of the system is a triaxial core holder, capable of applying up to 10,000 psi axial and radial confining pressure to the core samples. It is designed to hold cores 1 inch in diameter and up to 24 inches long, and accommodates single-phase and two-phase flow at static fluid back-pressures up to approximately 9,000 psi. Constant-flow-rate pumps are used to produce pulse-free flow of oil and water mixtures through the cores. Currently, accurate flow rates of 0.02 to 800 cc/min can be achieved. Stress cycling at frequencies from DC to approximately 2000 Hz are generated by direct mechanical coupling of the core to a Terfenol-D magnetostrictive actuator attached to one end of the core holder apparatus. The actuator can deliver dynamic force as high as ±200 lbf P-P with a maximum displacement of ±0.002" P-P. Thus, we can create Young's mode strains as high as approximately 10^{-4} in a 1-inch-diameter sandstone core. Permeability of the core samples is obtained by measuring the pressure drop across various sections of the core during constant flow. A load cell in series with the actuator and core provides calibrated measurements of applied stress and strain gauges attached to the side of the core allow dynamic measurements of Young's modulus to be made during stress excitation of the samples.

2-phase fluid experiments were completed on stimulated enhancement of oil and brine flow for different flow-rate ratios. The results for changes in bulk fluid pressure drop during stimulation are shown in Figure 2. Stress stimulation increases the pressure drop across the core regardless of the oil-to-brine flow rate ratio. However, the amplitude and duration of the pressure increase appear to depend on the flow rate ratios. The results may indicate that stress stimulation causes water-wet rocks to become more oil wet, thus trapping additional oil. If this is the case, it is likely that reservoirs that are at least partially oil wet will respond better to stimulation treatments than water-wet reservoirs. This is because, for oil-wet reservoirs, the treatment may cause formation water to be trapped and thus increase the oil cut.

For the water flooding tests a custom oil/water separation column was used to measure real-time changes in oil and water production history during drainage and imbibition runs. Numerous flooding runs were performed with brine and 10-weight oil. The resulting data indicated that stimulation enhanced brine production during the oil floods and decreased the net oil displaced during water floods. These observations agree qualitatively with the 2-phase flow tests described above. Although contrary to the desired effect, discussions with industry partners indicate that the hypothesis of altered wettability may be reasonable because there are numerous examples of oil reservoirs that are in a state of mixed wettability and it is likely that some of the successful field stimulation tests reported were conducted under these conditions. More accurate characterization of field conditions for future reservoir stimulation tests, as well as results from future laboratory tests on oil wet cores may help confirm this hypothesis.

Field Stimulation Tests and Results

Several field tests were conducted at the Lost Hills field in Central California in the Diatomite formations. In these tests a downhole fluid pulsation source, provided by Applied Seismic Research, was placed in a well at approximately 800 feet depth and activated with pumping rods from the surface. This device creates a classic hydro-impact pulse wave with an amplitude of 4000-5000 psi in the wellbore fluid which travels down the well and out into the formation through the perforated casing at 2200 to 3600 foot depth. The hypothesis is that this pulse of energy is strong enough to stimulate the reservoir and mobilize trapped, unswept oil reserves. An initial 12-day stimulation test was conducted with this device during July 2000. Forty-six test wells at distances from 200 feet to 2300 feet showed increases in oil production and oil cut during stimulation. It is interesting to note that there was no overall increase in fluids, just an increase in the oil cut, which is what has been observed in other successful cases of stimulation. A longer test was conducted for 38 days during October - November 2000. At the beginning of this second test the production increase caused by the first 12-day test was starting to decline again. Two groups of wells were monitored for production changes. A group of 60 wells showed an increase in oil cut of 11% and an increase in oil production of 17%. However, many of these wells had undergone various types of workovers, including stimulation by fracturing, within the previous year and it was felt that this activity may have contributed to the observed production increases. Because of this, a subset of 26 control wells were selected which had not been disturbed by other types of conventional stimulation procedures to determine the effect of the hydro-impact source alone. By the end of the second stimulation treatment these 26 control wells showed and increase in total coil cut of 29% and the total oil production had increased by 26%. These results are shown in Figure 3.

In reviewing the historic production data for the control set of 26 wells, it was noticed that there was an apparent increase in production that occurred during the magnitude 7.1 Hector Mine earthquake on October 16, 1999 in the Mojave Desert, which is about 230 miles away from Lost Hills. As shown in Figure 3., the earthquake caused an increase in oil cut of 24% and an increase in oil production of 20%. This response is similar to that caused by the 50 days of downhole seismic stimulation. We estimated the ground motion caused at the surface of the Lost Hills field by a 7.1 event at 230 miles distance would be on the order of 1 mm. The acceleration at 1 hertz would be about 0.1 percent of gravity. The energy reaching the Lost Hills reservoirs from this earthquake is assumed to be much larger than that generated by the hydro-impact source. Thus, since the source appears to have increased production, the threshold of seismic stress required to stimulate production in this case is much less than that generated by the earthquake. However, the cumulative energy delivered to the reservoir by the hydro-impact source may be similar because it was applied continuously over a long period of time.

The source measurements from the seismic monitoring will allow us to better quantify the stress threshold and total energy requirement. A three level geophone and hydrophone lowered to the reservoir level is being used to record the seismic energy. With these data we can then accurately observe the level and bandwidth of the wavefield as it propagates through the reservoir. In addition to the propagating seismic wavefield, the hydro-impact pulses generated in the source well are being measured by placing a wide-bandwidth, large-dynamic-range pressure transducer in the perforated section of the source well. This will provide the source function and energy output generated at the reservoir level.

Stress-wave induced changes in oil flow behavior

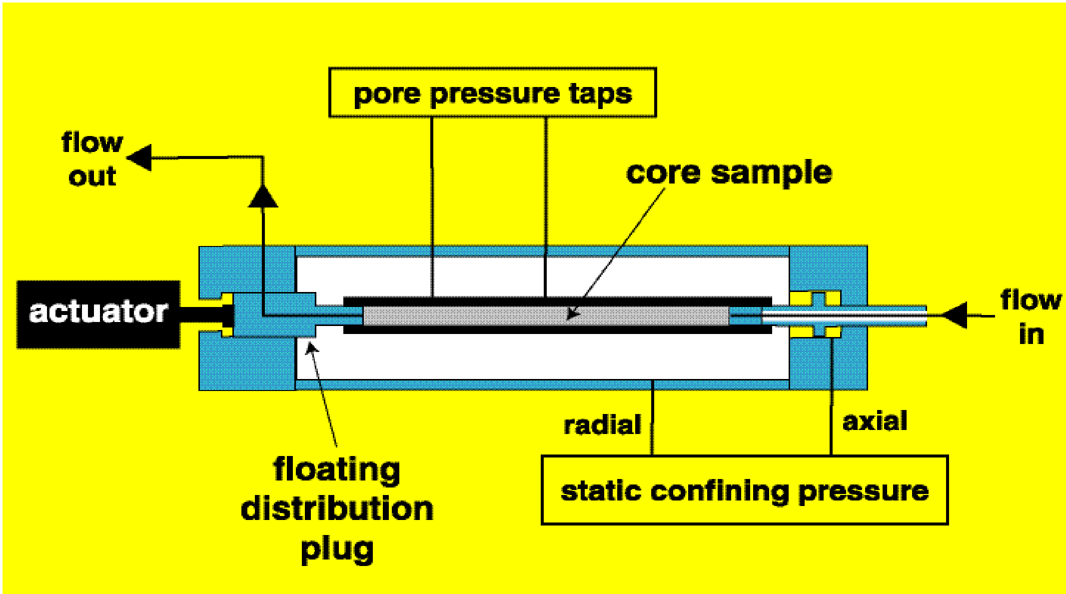

Figure 1. Schematic diagram of the core flow apparatus used for testing mechanical stress stimulation of 2-phase fluid flow behavior in the laboratory. Details of the apparatus are described in the text.

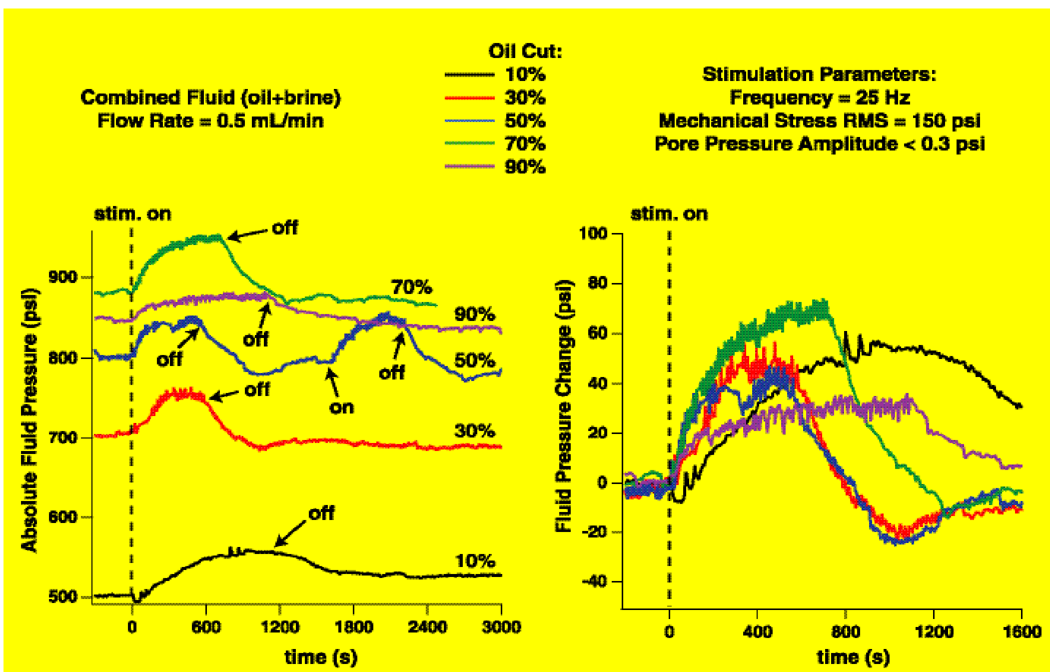

Figure 2. Pressure drop data measured during 2-phase oil/brine steady-state flow through Berea sandstone. Percent oil flowing is indicated by the colors. Episodes of stress stimulation are indicated by the dashed line and labeled arrows.

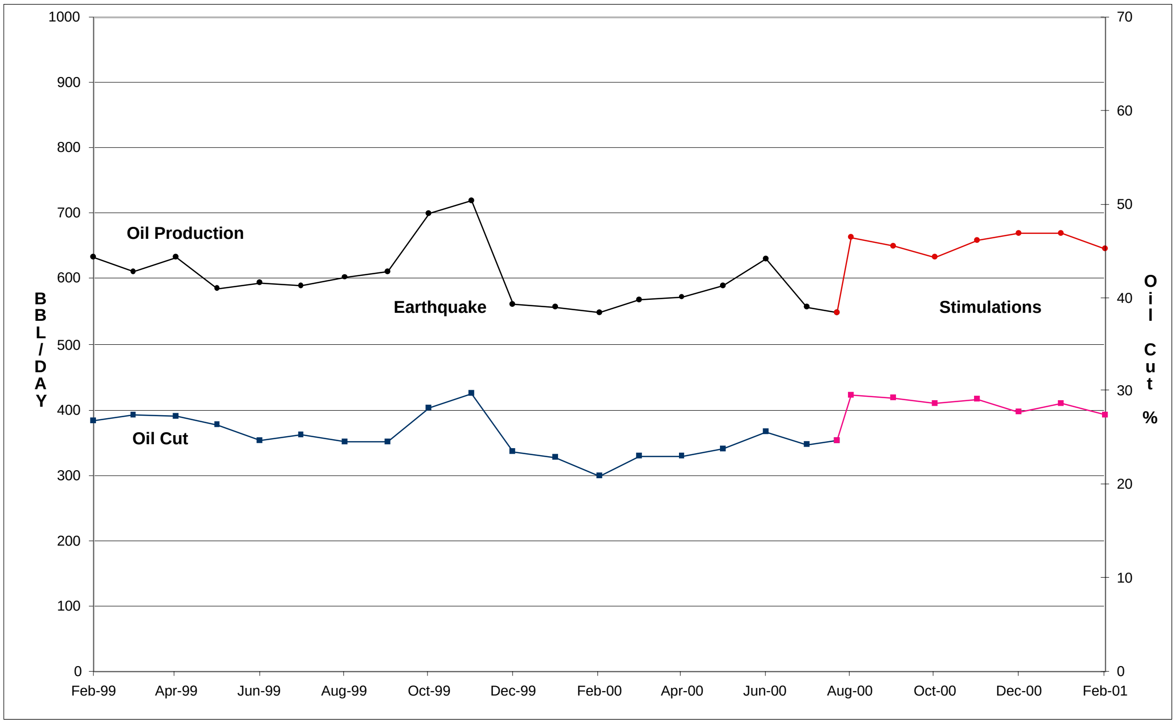

Figure 3. Oil and oil production data compiled for controlled subset of 26 producing wells from the Lost Hills field, California. Historic production data show a clear response to a magnitude 7.1 earthquake in October 1999 and to downhole stimulation treatments performed during July - November 2000.

Conclusions

The results presented here lend further credibility and quantification to the well-established phenomenon that low-frequency stress waves in the Earth can, under appropriate physical conditions, enhance the transport of oil in marginal reservoirs. Despite the growing experimental evidence, however, the fundamental science and physical mechanisms governing the phenomenon remain poorly understood. Ongoing research should eventually allow this important EOR technology to be further developed to the point where its results can be predicted reliably in the field.

Acknowledgements

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