Real-time completion monitoring of deepwater wells: Part I - Modeling and first experiments

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Summary

We describe Real-Time Completion Monitoring (RTCM), a new non-intrusive surveillance method for identifying permeability impairment in sand-screened completions that utilizes acoustic signals sent via the fluid column. These signals are carried by tube waves that move borehole fluid back and forth radially across the completion layers. Such tube waves are capable of "instant" testing of the presence or absence of fluid communication across the completion and are sensitive to changes occurring in sand screens, gravel sand, perforations, and possibly reservoir. The part of the completion that has different impairment from its neighbors will carry tube waves with modified signatures (velocity, attenuation). The method would require permanent acoustic sensors and thus, it could be thought of as "miniaturized" 4D seismic and "permanent log" in an individual wellbore.

Introduction

Completions lie at the heart of deepwater production and constitute a large portion of the overall well cost. Great multidisciplinary effort is put upfront to design them right. This contrasts greatly with the production stage where little information is available to detect problems, optimize the inflow and prevent expensive workovers. Sand screen plugging, incomplete packing, development of "hot spots" in screens, destabilization of the annular pack, fines migration, near-wellbore damage, crossflow, differential depletion, compartmentalization, compaction represent a typical list of challenges that are extremely difficult to decipher based on just several permanent pressure and temperature gauges (Wong et al., 2004). The often discussed issue of "well underperformance" in the Gulf of Mexico (Wong et al, 2003) absorbs large-scale reservoir issues such as compartmentalization as well as changes in local well skin with time that further comprises of completion, perforations and near-wellbore effects. Existing sparse data from wells can support many of these scenarios confirming that the problem is underconstrained. In the context of deepwater completions there is an additional emphasis on sand control because it is believed that "Managing produced sand, as we understand it, is generally a costly and mostly unworkable solution for the Gulf of Mexico, but can work well in other places where there is some grain-to-grain cementation present" (Scott Lester of Shell, Sand Control, 2006, p. 4).

The aim of this study is to develop new method, Real-Time Completion Monitoring (RTCM), that can characterize permeability impairment of the sand screen, gravel, perforations and the immediate near-wellbore space.

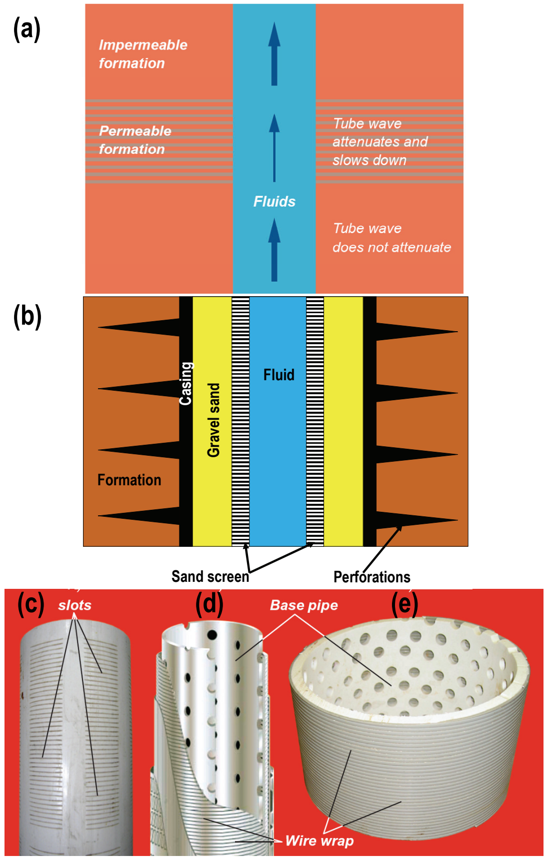

Figure 1: (a) The tube wave attenuates and slows down when it encounters the permeable interval that can exchange fluids between borehole and formation. (b) Schematic cross-section of a sand-screened completion in deepwater well. Sand screens: c) slotted PVC screen used in this experiment; d) a premium screen, named as Excluder (from Baker), e) wire-wrapped PVC screen.

Principles

Physical principles allowing estimation of permeability from acoustics waves are well-known for open boreholes where "permeability from Stoneley wave" became the only "direct" technique of estimating in-situ permeability from wireline logs (Tang and Cheng, 2004). A tube or Stoneley wave is a fundamental axisymmetric mode that represents a piston-like motion of the fluid column resisted by the borehole wall. When tube waves encounter a permeable region, their signatures change since the radial motion of the fluid is no longer fully resisted by the borehole wall and part of the fluid can escape in and out of the formation

(Figure 1a). This implies that tube-wave velocity decreases and attenuation increases with increasing fluid mobility (permeability/viscosity). RTCM extends ideas of open-hole Stoneley-wave logging to wells with sand-screened completions typical for deepwater. These wells have additional layers between the formation and borehole fluid such as sand screen, gravel sand, and casing (Figure 1b). The sand screen and gravel pack prevent migration of reservoir sand into the wellbore and maintain the integrity of the reservoir around the wellbore. Completed wells have one essential similarity to the open-hole model: in a normal scenario of a flowing well there has to be fluid communication across all layers of the completion. The aim of the current study is to analyze the effect of broken fluid communication across the sand screen (or perforations) through the signatures of tube waves.

RTCM concept

Figure 2 depicts two possible configurations of the RTCM method: "repeated or permanent log" (transmission) and "mini-4D seismic in a well" (reflection). In both cases we detect changes in acoustic signatures of tube waves over time and infer changes of permeability along the completion. In the transmission configuration we measure velocity and attenuation of the tube waves(s) along the completion and thus need sensors along the sandface (Figure 2a). In the reflection configuration we need sensors only above the completion and analyze the change in reflected arrivals from permeability interfaces (Figure 2b).

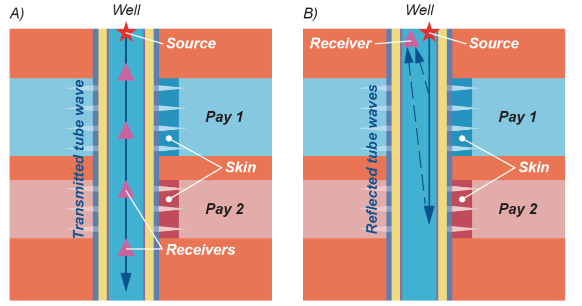

Figure 2: Conceptual design of RTCM configurations: a) "Repeated or permanent log" (transmission configuration); b) "Mini-4D seismic in a well" (reflection configuration).

It can be shown (Bakulin, 2008b) that such measurements can be performed while the well is flowing, thus providing valuable information in real time to well engineers and production technologists. Such information allows them to:

- detect changes in permeability in and around the well (and thus the inflow ability) in real time
- identify the well structure responsible for any problems (screen, perforation etc)
- design best practices for drawing the wells without impairing them
- raise red flags early on when problems are not acute and can be fixed with lighter effort
- characterize cross-flow and differential depletion in wells with multiple commingled producing intervals.

Here we report on a full-scale laboratory test of the RTCM concept when permeability impairment is caused by sand-screen plugging in a completion without gravel pack.

Full-scale laboratory test

Schematics and an actual photo of the horizontal flowloop setup used for experimental measurements are shown in Figure 3. The outer pipe (casing) is modeled with a glass pipe. The inner pipe (PVC sand screen) is positioned inside using plastic centralizers. To model an open sand screen ("open pores") we use a PVC pipe with 0.0002 m slots (Figure 1c). The plugged sand screen was modeled with a blank PVC pipe without slots and is referred to as "closed pores". The annulus between the inner and the outer pipe is filled with water. Measurements are conducted with 24-level a hydrophone array (35 cm spacing) and a piezoelectric source, both lying down at the bottom of the inner pipe.

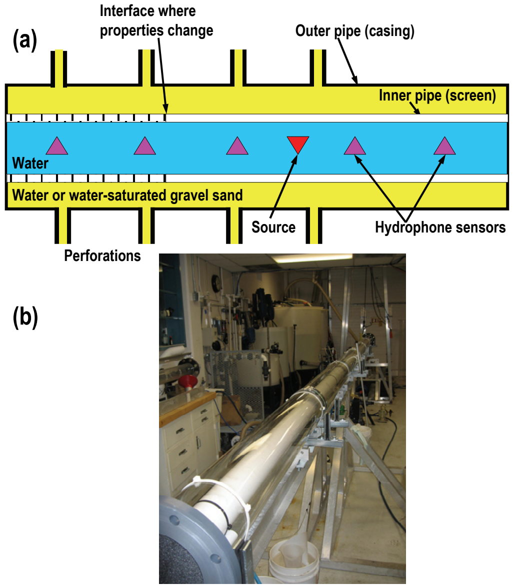

Figure 3: (a) Sketch of the flowloop setup with the model of sand-screened completion in horizontal well. (b) Photograph of the actual setup with a glass outer pipe (no perforations).

Idealized completion model

Actual sand screens can be quite complicated (Figure 1d), but we assume that a screen can be represented by a homogeneous effective pipe, both in terms of mechanical and hydraulic properties. If this pipe is not permeable (plugged screen) then the laboratory setup can be simplified to this idealized four-layered model: fluid - elastic inner pipe (screen) – fluid – elastic outer pipe (casing). This model of two concentric elastic pipes with a free outer boundary supports four axisymmetric wave modes at low frequencies (Bakulin et al., 2008a):

- TI – tube wave supported by the inner pipe
- TO - tube wave supported by the outer pipe
- PI - plate (extensional) wave related to the inner pipe
- PO – plate (extensional) wave related to the outer pipe

Figures 4 show synthetic seismograms for a four-layered model similar to experimental setup. The dominant arrival is a fast tube wave associated with the outer pipe (TO), whereas the slow tube wave supported by the inner pipe(TI) is weaker. If the inner pipe becomes permeable (open to flow sand screen) then both tube waves experience attenuation and slow-down.

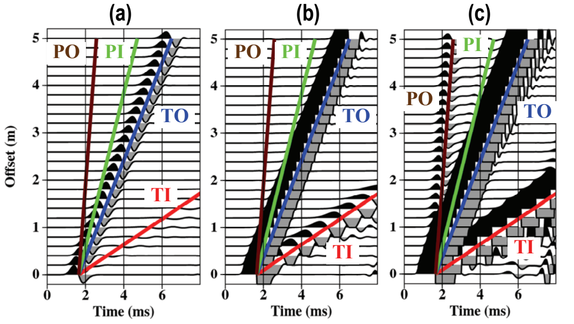

Figure 4: Pressure seismograms with successive amplifications for a four-layered model with closed pores (no gravel pack) using model with glass outer pipe and plastic inner pipes. (a) The largest arrival is a fast tube wave (TO - 1030 m/s) related to the outer glass pipe. (b) The smaller arrival is a slow tube wave (TI - 270 m/s) related to the plastic inner pipe. (c) Plate waves are of even smaller amplitude (brown PO - 5410 m/s, green PI - 1630 m/s).

"Permanent or repeated log" (transmission)

Let us first focus on transmission signatures – velocity and attenuation – in the presence of open and plugged screens. Figure 5a shows the raw data recorded in the case of no screen and a screen with "open" or "closed" pores. Despite pipe joint reflections, there are clear differences between three scenarios. First, in the absence of a screen, there is only one (fast) tube wave present with velocity of about 1050 m/s. It experiences some amplitude loss, possibly due to intrinsic attenuation in the recording cable. When an impermeable inner pipe is added (closed pores) a slow tube wave appears, and the fast tube wave becomes more attenuative. When the inner pipe becomes slotted (open pores) then fluid on both sides of the PVC screen start to communicate, and this leads to a very strong attenuation of both tube waves. Thus a greatly increased attenuation of both fast and slow tube waves is the first-order diagnostic for open screens, whereas reduced attenuation is characteristic for plugged screens. Additional diagnostics can be established by analyzing energy distribution as a function of frequency between these two cases. Figure 5b shows slowness-frequency displays. Both fast and slow tube waves with approximately the same velocities of 1100 m/s and 350 m/s are clearly seen in the plugged and open cases, however the slow wave is completely absent without a screen. In a plugged screen the fast wave carries maximum energy in the frequency range of 300-600 Hz close to the dominant frequency of the source, whereas lower and higher frequencies carry less energy. In contrast, the spectrum of the fast wave in an open screen has a big energy "hole" between 300 and 600 Hz where the fast wave is attenuated so strongly that even higher frequencies (600-900 Hz) carry more energy. This behavior suggests that fast-wave energy is severely attenuated in the medium frequency range whereas it is still preserved in the high-frequency range.

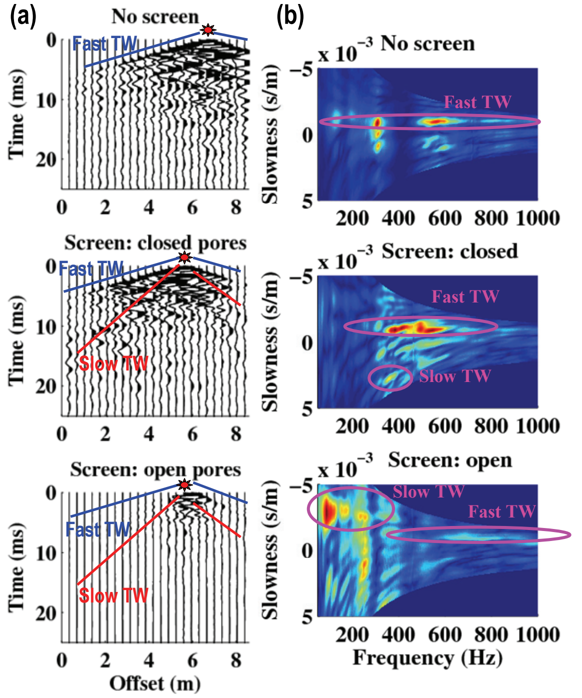

Figure 5: Seismograms (a) and slowness-frequency displays (b) of experimental data. "No screen" shows traces in the absence of an inner pipe. "Open pores" is for a slotted sand screen, whereas "closed pores" is for a blank pipe (no slots). Note that the fast tube wave is least attenuated in the absence of a screen, attenuated in closed pores and substantially absorbed in open pores.

Let us compare this behavior with the poroelastic reflectivity modeling. Figure 6 shows synthetic seismograms computed for a glass setup. Sand screen is modeled as poroelastic Biot cylinder. The similar to the experiment, in the case of closed pores we observe two tube waves with the fast tube wave dominating in amplitude. In the presence of a screen with open slots both waves experience strong changes. The fast tube wave experiences moderate attenuation and change of waveform.

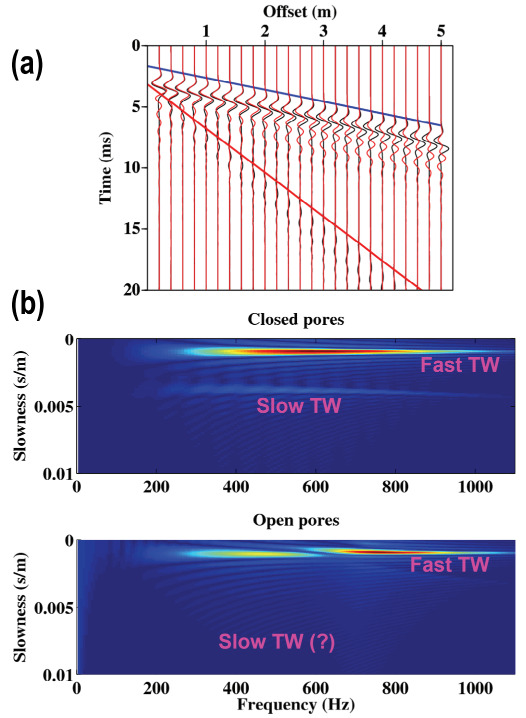

Figure 6: Synthetic data computed for open and closed pores in the glass setup. (a) Overlay of pressure seismograms for open (red) and closed (black) pores showing that the fast tube wave in a permeable screen experiences attenuation and dispersion. Blue and red lines denote moveout velocities of the fast (1030 m/s) and the slow (280 m/s) tube waves. (b) Slowness-frequency spectrums.

The slow tube wave transforms into a complex packet with weak amplitude. The following physical interpretation can be given to the modeled results. A tube wave is born when the piston-like motion of the fluid inside the pipe creates a radial expansion that is resisted by the elastic pipe. The slow wave is supported mainly by the inner pipe. When this pipe becomes slotted, radial movement of the fluid is no longer resisted since liquid can freely escape to the annulus, thus leading to a strong attenuation of this wave. In contrast, the fast wave is supported mainly by the outer glass solid pipe. When the inner pipe becomes permeable, piston-like motion of the fluid in the fast wave can additionally exchange the fluid between the outer and the inner fluid columns, thus creating a moderate attenuation.

Slowness-frequency spectra for open pores (Figure 6b) shows, that, similar to the experimental results the fast wave experiences anomalously high attenuation in the medium frequency range of 350-700 Hz. A more robust display averaging over "small", "medium" and "high" frequencies is shown on Figure 7. Comparison of Figure 7a and 7b confirms the qualitative agreement between experiment and modeling: in both cases the fast wave exhibits anomalous amplitude decrease in the medium frequency range, while still preserving higher and lower frequencies. This amplitude decrease should be attributed to anomalous attenuation caused by fluid movement through the slotted porous screen. The frequency range with resonance attenuation is controlled by permeability, i.e. the lower the permeability, the higher the frequency of the band with anomalous attenuation of the fast wave. Therefore central frequency of the band with anomalous attenuation of the fast tube wave is an additional useful diagnostic of the screen permeability.

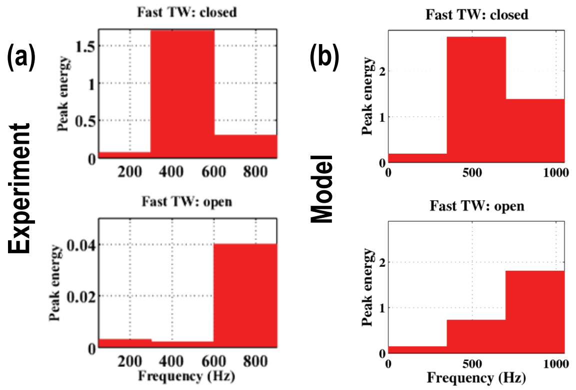

Figure 7: Experimental (a) and modeled (b) distribution of energy of the fast tube wave. Note anomalously high attenuation in the "medium" (~300-700 Hz) frequency range due to permeability of the screen.

Conclusions

We propose a new non-intrusive real-time technique that monitors changes in permeability along sand-screened completions utilizing acoustic signals in the fluid column. We present a full-scale laboratory test verifying the method for a scenario where impairment is caused by sand-screen plugging in a completion without a gravel pack. We observe two tube waves supported by the screen and casing Simple inspection of the raw data allows identification of plugged and open sections of the screen: plugged sections give large signal, whereas open sections have a lower signal (increased attenuation of both fast and slow tube waves). We further compared experimental results with simple poroelastic modeling and found a qualitative agreement between experimentally measured and predicted signatures. Experiments with gravel-packed completions are reported in a companion paper (Bakulin et al, 2008b).

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EDITED REFERENCES

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