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Water Hammer Effects on Water Injection Well Performance and Longevity

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Abstract

Water hammer effects resulting from the shutting in of water injection wells are an often ignored issue in petroleum production operations but they have considerable impact on injection well performance and longevity. Mismanaged, they can result in substantial and perhaps irreparable damage. This paper presents a study on the creation and propagation of water hammer due to rapid shut-in of water injectors.

Water hammer[1-4] or pressure surge, is a pressure transient phenomenon which has long been known to occur as a result of a sudden change in fluid flow velocity. In water injectors, rapid shut-in creates a water hammer. Over time, injectors that undergo repeated rapid shut-ins often have significantly reduced injectivity and show evidence of sanding and even failure of the down-hole completion[5]. It is therefore critical to understand the nature of water hammer including the magnitude, frequency, and energy dissipation.

To study the water hammer in water injectors, a field trial was conducted to record pressure pulses generated from rapid shut-ins, at different well depths, in a soft formation, cased and perforated (C&P) water injector. Modeling work was conducted to understand the data.

The results of the field trial and model work demonstrated that:

- The magnitude of the first pressure pulse due to abrupt shut-in can be estimated by using the equation: $\Delta p = V \times \rho \times c$, where V is the flow velocity, ρ is the fluid density, and c is the speed of propagation of a pressure signal along the well.
- High rate sampling (up to 100 samples/second) is required to capture subtle details of the water hammer signal.
- Water hammer can be modeled as a low-frequency pressure wave similar to the higher frequency Stoneley waves produced during VSP's and by acoustic logging tools.
- Models of water hammer propagation in a synthetic analog of the test well reproduced most of the details of the signals recorded during the tests.

Introduction

Water injectors have become increasingly important in recent years as maturing oil production has come to rely on water injection to maintain high rates from reservoirs with low reservoir energy and sand production issues. There are many reported studies of sand production in producers[6-12] but very few discussions of sanding issues in water injectors[5, 13-15]. Several factors, including repeated cycles of injection and shut-down, crossflow, backflow, and water-induced strength reduction, are known to cause sanding in injectors. One important but under-studied factor is the damage induced by water hammer (WH) pressure pulses, which may produce cyclic pressure variations of hundreds of psi.

In weak sands, fluid pressure fluctuations in the near-wellbore as small as a few tens of psi may be sufficient to cause sand failure[14]. A recent modeling study[5], summarized in Figure 1, shows that for an unconsolidated rock the combination of WH and injection pressure creates more sanding than a monotonic increase in injection pressure with the same equivalent total injection pressure. The additional sanding is attributed to the faster rate of formation degradation in response to the more frequent pressure pulses, which is demonstrated in Figure 2.

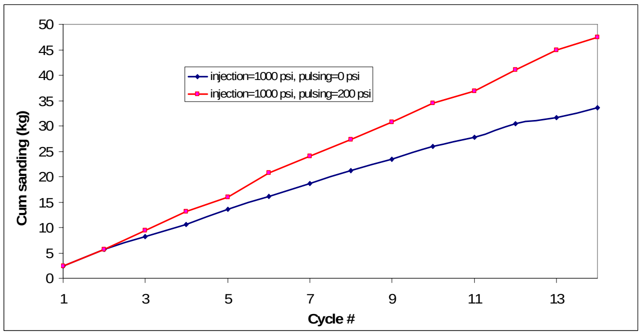


Figure 1. The Influence of WH Pulses on Computed Sanding[5]

Figure 2 shows the cohesion degradation (solid symbols) and cumulative sand volume (open symbols) for an injection pressure of 1,000 psi and various levels of WH pressure pulses for rock with a UCS of 140 psi. As expected, larger WH pulses cause faster strength degradation which in turn hastens the onset of sanding and increases its rate. However, for the same rock, when WH pulses of 500 psi have a dramatic impact on sanding, the difference between WH of 200 psi and no WH is far smaller than that might have been suspected. These results indicate that for a given rock and injection pressure there is a threshold, below which WH may not have an appreciable detrimental impact. Published field observations[13,14] support that water hammer can have a pronounced impact on sanding especially in unconsolidated formations

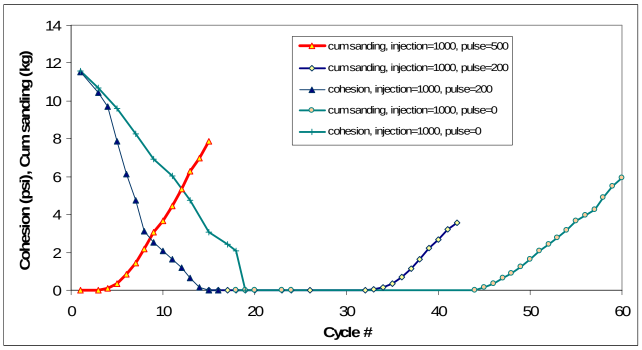


Figure 2. Material Degradation and Sanding Prediction at Given Conditions[5]

The objectives of this study was to measure the wellbore pressure surges resulting from rapidly shut-in a soft formation C&P water injector at various points in the wellbore and to capture the magnitude and frequency of the pressure pulses versus time. The goal was to begin to understand how water hammer propagates in a complex well, and is affected by parameters that are under the control of production and completion engineers.

Water Hammer Field Trial

To study the creation and propagation of water hammer due to injector well shut-in, a field trial was conducted in December 2005 in a cased and perforated (C&P) injection well.

The selected well, shown schematically in Figure 3, is open to 4,696 ft (all depths mentioned in this paper are measured depth unless it is specified otherwise). It is completed with 7 inch. casing perforated over 4,532-4,543 and 4,576-4,596 ft, and has 3.5 inch tubing extending to 4,310 ft. Maximum deviation is 34 degrees at 2,680 ft, and less than 2 degrees at the perforations.

Before initiating the test sequence, it was verified that measurable WH signals were generated at flow rates that did not jeopardize the well or the surface equipment, and did not place undue stress on the downhole gauges or their connection to the wireline.

Operational Procedure. Below is the summarized procedure:

- Step 1: Well Preparation: The well had been shut-in since August 2005. Thus the first step was to clean out the well, tag bottom and re-establish injectivity.

- Step 2: Step Rate Test: The purpose of this step was to determine the proper test injection rates and pressures.

- Step 3: Generate and Measure Water Hammer Events: A set of downhole pressure gauges was lowered into the well. Three predefined depths (4,450, 2,500, and 750 ft), were selected. At each depth, a safe and stable injection rate of approximately 2200 bwpd at a wellhead injection pressure of ~1100 psi was established, after which the well was shut in by closing a quick-acting (~ ½ second to closure) valve. The downhole gauges recorded pressure as a function of time at 100 samples per second and a precision of 1 psi. The WH event was generated twice at each test depth for quality control purposes. Six sets of signals were recorded (see Table 1).

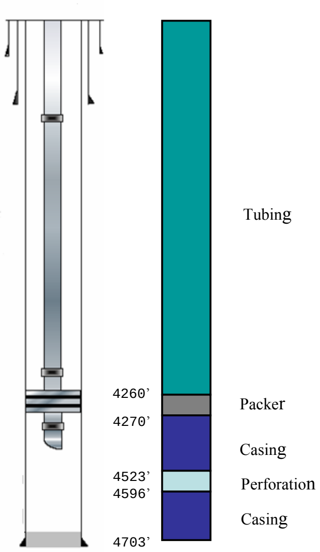


Figure 3. Schematic of the Well and Completion Configuration

Test	Depth, MD	Injection Recording Period, min	Shut In Recording Period, min	Notes:
1	4450'	10	10	To record water hammer near perforations
2	4450'	10	10	To evaluate repeatability of signal
3	2500'	10	10	To record water hammer in 3-1/2" tubing
4	2500'	10	10	To evaluate repeatability of signal
5	750'	10	10	To record water hammer in 3-1/2" tubing
6	750'	10	10	To evaluate repeatability of signal

Table 1. Summary of Pump Schedule

Pressure pulses were also recorded by using a pressure transducer mounted on the surface. Following the tests, a sample of fluid from the well was obtained for analysis of physical properties.

Recorded WH Data at Depth of 4,450 ft. Figure 4 shows the data from the first two WH events (Tests 1 and 2), recorded with the transducers at 4,450 ft, in the casing immediately above the topmost perforated interval. The first trace is reproduced in red, overlain on the second trace, for comparison purposes. There is a slight difference in the pulse amplitude – Test 2 had slightly higher amplitude than the first test – but otherwise, and except for the higher-frequency noise and a slightly more rapid mean pressure drop in the second test, the signals are virtually identical. It is important to note however that the absolute pressure, which is a function of the total amount of injected fluid and the rate and injection pressure prior to pump shut-down, is slightly lower in the second test.

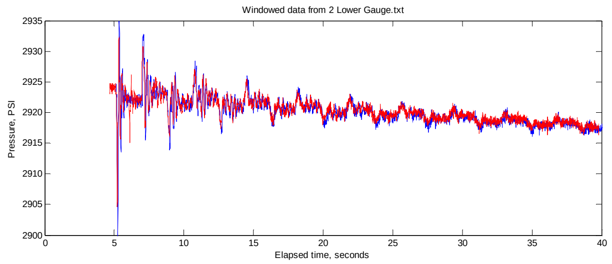
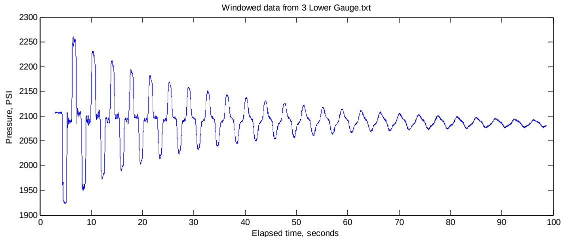
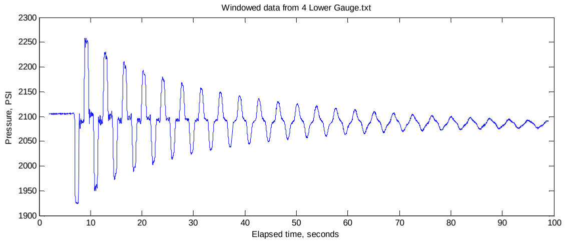


Figure 4. Processed Data from Tests 1 (Red) & 2 (Blue) with the Downhole Gauges at 4,450 ft

Recorded WH Data at Depth of 2,500 ft. The second set of WH events (Tests 3 and 4) recorded at 2,500 ft are shown in Figure 5. These were also very similar to each other, demonstrating that it is possible to produce repeatable signals using the equipment provided for this test.



a). Data from Test 3



b). Data from Test 4

Figure 5. Data from Tests 3 and 4 Recorded with the downhole Gauges at 2500 ft

Recorded WH Data at Depth of 750 ft. Figure 6 shows the data from Tests 5 and 6, recorded with the transducers at 750 ft inside the 3.5 inch tubing. As in Figure 4, the first trace (Test 5) is reproduced in red, overlain on the second trace (Test 6), for comparison purposes. Again there is a slight difference in the pulse amplitude – the first test has slightly higher amplitude than the second test over the entire time shown – but otherwise, and except for the higher-frequency noise seen on each test, the signals are virtually identical. These signals, and those recorded at 2,500 ft shown in Figure 5, are 10 times larger than those recorded within the 7 inch casing at 4,450 ft.

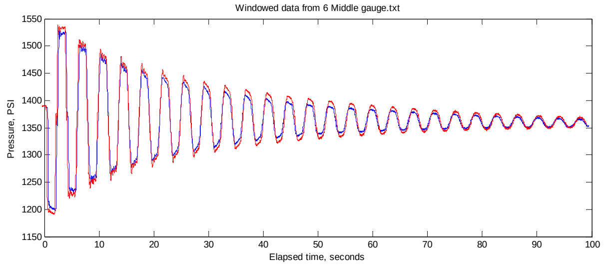


Figure 6. Signals Recorded from Tests 5 (Red) & 6 (Blue) at 750 ft

In summary, the data shown in Figures 4 to 6 indicate the high quality of the signals recorded during these tests. While there were some minor differences presumably due to small differences in the test conditions (flow rate into the well; downhole pressure; valve closure rate) the repeated tests are remarkably similar. Also, the data recorded on the middle gauge and on the upper gauge (2.5 ft apart) from the same test are virtually identical, indicating excellent calibration and that the position of the gauge in the string is not important.

Measured data also showed that high frequency was generated to above 17 Hz which indicates that adequately reproducing the signal at this depth requires sampling at least as fast as twice the period of a 17 Hz wave, or (rounding up) that sampling should occur at least 40 times per second. From this perspective the sampling rate of 100 samples per second was quite reasonable and has become the preferred sampling rate for future tests in other wells.

Comparison of the Field Results to Theoretical Predictions

Models were built to simulate the creation and propagation of the water hammer and found to be able to reproduce the principal characteristics of the recorded signals.

Most previous models for water hammer have been adapted from pipeline modeling, where the conduit is surrounded by air. They cannot handle formation / completion effects[17]. Here the effects of a well on water hammer propagation are analyzed by using Stoneley wave models. The method is to model the water hammer pulse as a propagating wave (a tube or Stoneley wave) whose characteristics can be described using classical theories of wave propagation in wellbores that have been developed over the past 30 years. The Stoneley wave is a borehole guided wave with most of its energy in the wellbore fluid, and is an evanescent wave in the formation. Its velocity is controlled by the effective shear modulus of the formation/wellbore system, and by the hole size, fluid density and fluid compressibility.

Models of water hammer propagation in a synthetic analog to the test well reproduced most of the details of the signals recorded during these tests. The describes water hammer as a propagating step-function pressure pulse that initiates at the shut-in valve due to the abrupt change in flow velocity when the valve is closed. A similar (positive) pressure pulse presumably is created upstream of the valve but was not studied during this test.

It is well known that the pressure generated by rapidly closing a valve is related to the flow velocity times the inertia (density times wave propagation velocity) of a propagating pressure pulse in the fluid-filled well[1-4]. Explicitly,

$$\Delta p = V \times \rho \times c, \tag{1}$$

where $\boldsymbol{V}$ is the flow velocity, ρ is the fluid density, and c is the speed of propagation of a pressure signal along the well.

The first step in modeling the WH signal recorded in this field trial is to determine whether this approach to estimating the pressure step is valid. Using the given (volume) flow velocity of 2200 bpd, the inner diameter of the tubing (drift) of 2.867 in., and the density of water at ambient temperature of 1040 kg/m^3, and $c \cong 1350$ m/s, the propagation velocity of the pressure pulse predicted by the synthetic modeling and measured in the well, the pressure pulse due to rapid valve closure should be approximately $\Delta p = -198$ psi, very close to the initial downward pressure change shown in Figure 6, the shallowest recording of the water hammer signal in the field trial.

Synthetic modeling was carried out by matching the signal amplitude of the downward-going first pressure step at the shallowest depth (which was approximately as predicted using Eqn. 1), using the computed propagation velocity of the signal along each section of the well given the measured mud properties and the known well design, and comparing the predicted decay rate, the predicted time delay between signals and the predicted signal shapes to those recorded in the well. The well was simplistically assumed to consist of a series of connected sections with different properties (see Figure 3). These were the tubing section, the packer at the base of tubing, the cased hole, the perforations, and the cased hole below the perforations. The perforations were modeled as a single interval.

The results are shown in Figure 7 for the data at 750 ft, and in Figure 8 for the data recorded at 4,450 ft. Here blue curves represent modeling results. Red and light blue curves represent recorded field data. It is clear that the timing of the arrivals is nearly identical in the model compared to the actual data. However, it is apparent in the results from 750 ft and more obvious in the results from 4,450 ft that the amplitude decay is slightly different in the synthetic than in the field data.

Models that included the change in effective well diameter from the 3.5 inch tubing to the 7 inch casing accurately reproduced the more than 90% reduction in pressure due to the propagating pressure pulse. These latter models reproduce the overall shape of the signals within the tubing, and reveal that the energy reduction is due to effective transmission losses caused by the change in diameter at the base of the tubing.

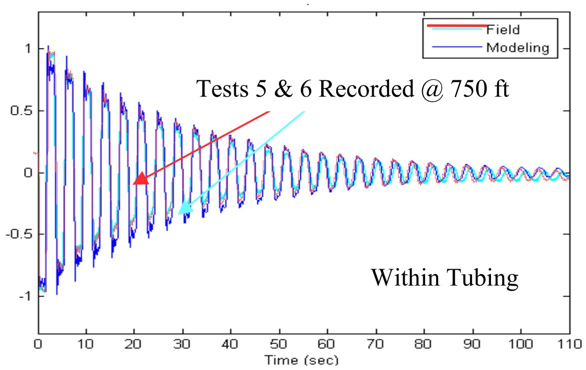


Figure 7. Comparisons of Synthetic and Actual Recorded Data at 750 ft during Tests 5 and 6

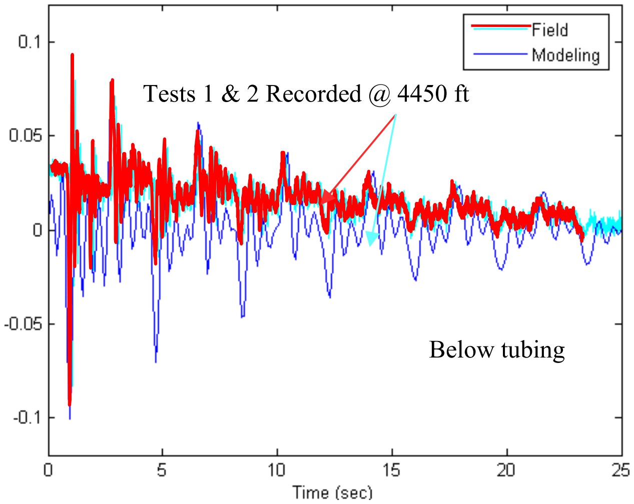


Figure 8. Comparisons of Synthetic and Actual Recorded Data at 4,450 ft during Tests 1 and 2

Discussion of results

It is worth to note the reduction in water hammer magnitude at lower depth (4,450 ft) in the well and thedirect linkage to well geometry. Other well geometries are not as benign as in this test well.

Signals from gauges at different positions were virtually identical, and there was no evidence of signals reflected from the gauge package in the collected field data. That indicates the presence of the gauges in the well did not affect the recorded signals. Furthermore, theoretical models run without including the gauge package as part of the well system matched the data to a remarkable degree.

It is very interesting to see the comparison, shown in Figure 9, of the actual recorded signal in the test well with a down sampled signal that would have been produced by a typical production gauge sampling at one sample every 5 seconds. The heavy red signal (generated by down-sampling the model data) overlain on the model data (shown on blue) clearly reveals that such under sampling severely distorts the data, as discussed above, and validates the need to sample water hammer signals at much higher rates than those are typically used for production data.

Figure 10 is a typical field data example of water hammer which was collected at 1 sample per 5 seconds. This data is highly undersampled, leading to severe aliasing and signal distortion. The time delay between apparent pulses of more than 30 seconds is much longer than the actual time lag expected for a multiply-reflected propagating signal, leading to the common misunderstanding of water hammer that it is an oscillatory “breathing” mode rather than a guided propagating wave. Also note that the amplitude of each pulse will be somewhat lower in under sampled data than in the actual one.

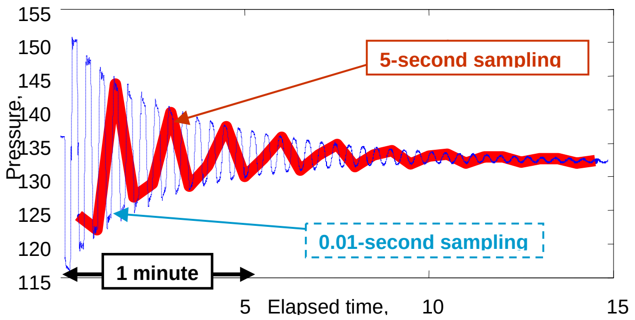


Figure 9. Comparison of Actual Data Recorded at 750 ft to What a 5-Second Sampling Interval Would Indicate

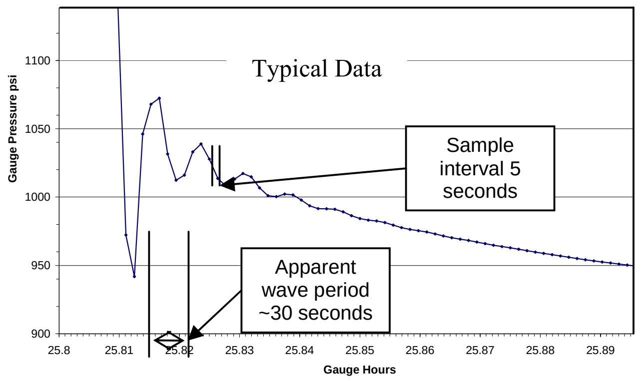


Figure 10. Typical Undersampling Data Collected in the Field

One way to reduce pressure transients in water injection well is to shut the well in slowly, which reduces the magnitude of the water hammer pressure pulse[1-4]. What was not clear is the precise nature of the variation in WH (including its magnitude, frequency, and energy dissipation along a well) as a function of shut-in rate and well design. The models developed and validated here with measured data can be used in optimizing the type and placement of hardware (e.g., pumps, chokes etc) and operational issues (e.g., rate of valve closure) to mitigate the most serious impacts of WH in a cost effective manner.

Conclusions

The data collected from this field trial was very unique and valuable to understand WH signals in water injectors. The results and comparison to modeling elucidate the mechanism of water hammer effects, and will help to determine if this is one of the key elements that cause sand face failure in injector wells. It will also provide information to design methods to minimize these effects.

Field trial results and modeling work showed:

- When shutting in a well abruptly (in this case, in less than 1 second), the magnitude of the first pressure pulse is not a function of the valve closure time. It can be accurately predicted by using standard models for which $\Delta p = V \times \rho \times c$, where V is the flow velocity, ρ is the fluid density, and c is the speed of propagation of a pressure signal along the well.
- Amplitudes of the first negative and positive going pulses at 750 ft below surface within tubing reached 200 psi below and 150 psi above ambient pressure. Signal amplitudes within the casing below the bottom of tubing (at depth of 4,450 ft) were one tenth the amplitude of signals within tubing. This is due to the changing in diameter at the base of the tubing.
- High frequencies were generated to above 17 Hz.
- Repeated signals at each depth were almost identical;
- No damage to the well was apparent as a result of these tests for this particular case.
- Modeling water hammer as a propagating low frequency Stoneley (tube) wave using realistic properties for the fluid and well completion accurately reproduced the timing of each pulse.
- Amplitude decay for the signal within the casing was less well reproduced.

The field trial demonstrated that

- Accurate reproduction of water hammer requires sampling at least 50 times per second.
- Simple theoretical analyses of water hammer creation were adequate to explain the initial drop in pressure associated with closing the valve. Subsequent pressure steps were reduced in amplitude relative to the initial step.
- The water hammer pressure signal is a propagating, multiple-reflected Stoneley wave, which can be modeled to provide predictions of the effects of completion design. Models using preliminary values of the properties of the perforated interval slightly underestimated the attenuation (decrease in pulse amplitude with time) that occurred in the well because the rock properties used were estimates.
- No damage to this well or to surface facilities resulted from a significant (nearly 200 psi at the surface) induced pressure pulse during this field trial. This does not mean, of course, that similar pulses in other wells will have similar effects. It appears in this case that the minimal influence of water hammer may have been due to the fact that the pressure seen at the perforations was reduced more than 90% compared to the pressure generated and recorded within tubing close to the surface.

Acknowledgment

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Nomenclature

Δp = magnitude of the first water hammer pressure pulse
V = flow velocity
ρ = fluid density
c = speed of propagation of a pressure signal along the well
L= length of the tube from valve to source

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