PRESSURE-TRANSIENT 3D IMAGING

Shockwave model reduces risk

A new well testing method calibrates the seismic reservoir image at a fraction of the cost

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Reservoir imaging adds value to an oil and gas property. A new pressure analysis method generates reservoir dimensions, limit distances and point-of-contact shapes from a family of slow-moving capillary shockwave fronts as they pass through the reservoir at slow diffusive speeds. A byproduct of the process is a running integration of fluid volume in place as the test progresses. This integrated volume can be used to develop information as to relative limit positions. This is made possible by the recognition of capillary bundles as physically constraining conduits of flow growing from the well and terminating in a step pressure shock front that acts as a moving boundary. Using these naturally occurring wave fronts can enhance the traditional use of pressure transient analysis as an evaluation tool. Capillary shockwave front imaging also can be performed throughout the life of a gas well to monitor the movement of a gas/water contact. If the relative position of one of four identified limits changes in a gas well with regard to the other three, it is probably a moving gas/water contact, since the fixed boundary limits will remain the same. A gas well can be retested with every operational shut-in to monitor each limit individually.

Technical summary

A shockwave front exists coincident with the traditional radius of investigation = $2(\eta t)^{1/2}$. It becomes the boundary condition for the cone of influence during the transient phase.

The capillary forces that give rise to the shockwave also constrain flow through radial capillary pathways that have finite strength. An example of the bounding shockwave is shown in Figure 1. Many attempts were made to reconcile this data using different simulators. The breakthrough came with the recognition that capillary pressure was playing a major role in limiting the rate of growth of the cone of influence. This led to a constrained capillary model.

The combination of radial pathways and the shockwave boundary condition produce discrete responses at the wellbore that are the result of First and Second Law requirements for Joule-Thomson hydraulic power dissipation through heat generation. When a section of the shock front encounters a change in permeability, the system responds by creating a secondary drawdown region within the original cone of influence. It is this secondary cone behind its own secondary shockwave that indicates the presence of a limit. Limits are encountered individually as the test progresses. The increased rate of pressure decay at the wellbore signals a limit has been encountered. The intensity of the change in pressure decay signals the shape of the limit at the point of contact relative to a straight line. Each limit can be described by distance from the well and by a bent line shape of known angular displacement. This allows point-by-point comparison of features on a geologic map. All pressure-transient analysis is based upon the homogeneous property assumption. The assumption is that the more heterogeneous a formation is, the more likely it will behave in a homogeneous manner. The shockwave overlay example was generated by limits that represented a shift from 500 md rock to 25 md rock. Better stated, all pressure analysis is a view of the reservoir relative to the cylindrical volume of the reservoir material around the well investigated during the midtime or infinitely acting radial flow period. Major anomalies appear as distortions in the growth process. Leaking or nonsealing faults and shale islands have characteristic responses when viewed from the perspective of the advancing shockwave.

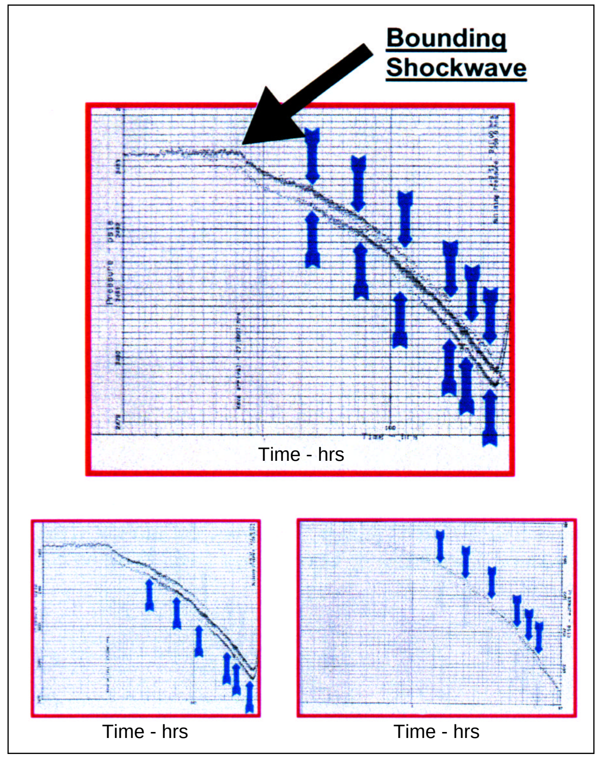

Figure 1.Constant flow rate test from two points of observation.

To reduce the capillary model to the traditional diffusion potential model, one only has to declare that all initiating pressures have broken down. A new physical model is traditionally placed in blind trials for evaluation. Every well test should be treated as an experiment. This requires that a best-fit geometric shape be developed without reference to a map. The blind geometric information can be compared with the geologic map to confirm its dimensional details both geometric and volumetric. Where the test and map differ, a reassessment of both studies can be focused upon the geologic aspect in question. For example, if a “blind” point-by-point assessment agrees on three out of four mapped limits, the efforts of the geologic engineering team can be focused upon the item in question. Often a question is raised as to whether a seismic feature is sealing. A transient test may be used to determine whether something changes at the

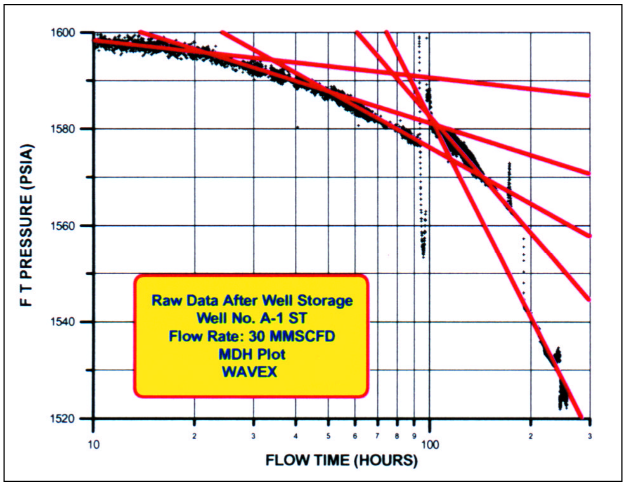

Figure 2. Well A-1 drawdown example.

radius of investigation for the feature in question. If the shock front passes through the feature with no corresponding response, it may not be material to the reservoir model. If reservoir continuity is in question, the use of overlapping tests may be used in lieu of a longer running interference test or an additional delineation well. In the case of transient reservoir models, each must be judged against a geologic and geophysical map and a track record of "blind" predictions.

Reservoir imaging

The use of 3D seismic has grown dramatically. This has resulted in much improved exploratory discovery ratios. However, as in all technologies, the new plateau of seismic technology is better than the old but remains imperfect. A comparable process that can explore the reservoir laterally from a wellbore is an excellent complementary technique.

Capillary shockwave fronts propagate from the wellbore when flow is initiated or a major rate change is imposed. These fronts are composed of many radial capillary pathways that grow coincident with the traditional radius of investigation. The small initiating capillary breakdown pressure that exists at each pore throat produces this physical phenomenon. The core laboratories have measured these pressure steps in the form of entry pressure and Haines' Jumps since their discovery in the 1940s. They have not been incorporated into transient reservoir models until now.

When these capillary ray clusters strike a reservoir boundary, they act in unison to provide specific information about that portion of the reservoir boundary. The capillary structure of the expanding cone of influence restricts the response of the system to reservoir limits in a radial isotropic manner. Fluid momentum stabilizes the cone of influence. When the cone encounters a limit, a secondary depletion region is formed around the wellbore to maintain the balances required by fluid momentum and the laws of thermodynamics. Because the system is composed of capillaries, each capillary acts much like a ray of light – a ray of light goes straight out and reflects off a boundary, while amplitude and frequency are factors of the boundary and its angle. A shape for each boundary contact can be developed to assemble an energy image of the reservoir that compares well with 3D seismic but at a fraction of the acquisition and interpretation cost.

In a process called pressure logging, the shock front capillary wave passes through the reservoir as Mother Nature's means for initiating flow. It is important to differentiate a capillary shock front from a sound wave. Sound causes the reservoir fluid and formation to vibrate. The shock front produces actual depletion. That is, the reservoir fluid moves from pore space to pore space, creating actual pressure decline. This pressure depletion wave is used to assess the reservoir volume, distance to limits and the point-of-contact energy equivalent shapes of those limits just as we would pull a resistivity logging tool across the face of a pay section to define its characteristics. This process is just as important as electric logging in early assessment of reserves. When a well is placed on production, it is possible to provide volume and reservoir dimensions that can be used to book reserves much faster than waiting for the production history to develop. In many cases, 2 days to 1 week of pressure data can tell the story. Small reservoirs test faster than large ones. The test duration is controlled by the volume required to assure a positive investment outcome or to confirm key limits on the geologic map.

The outermost or primary capillary shockwave propagates in a manner coincident with the traditional radius of investigation. As the capillary shockwave encounters an order of magnitude decrease in fluid mobility, the cone of influence responds within the constraints of the system of capillaries of which it is composed. Normally, a choke is used at the wellhead to maintain constant flow rate. The loss of growth at a sealing boundary results in the formation of a secondary cone of influence bound by its own secondary capillary shockwave discontinuity boundary. The new cone maintains constant flow by making up the flow loss from the nongrowing capillaries. The secondary boundary grows at a velocity commensurate with the growth of the outer or primary capillary shockwave boundary.

Testing method

The drawdown test conducted on a fixed choke bean is the preferred testing method. For wells already on production, a buildup followed by a drawdown provides two datasets that can be compared for pressure derivative shifts and singularities of the same set of reservoir limits or fluid mobility changes. Every time a well is shut in, then placed back on production, is an opportunity to test a well either from the surface or with a downhole pressure bomb. Wells producing substantial liquids should always be tested with a downhole gauge. Dry gas wells or wells that produce less than 150 bbl of total liquid per million standard cubic feet and flow enough to assure fluid unloading, are candidates for surface measurements. Resolution, accuracy and stability of the pressure recording instrument are essential to good testing practice. Mechanical bombs are best applied to low-permeability systems. The preference for smooth, reasonably constant-rate testing has to do with the fact that every time a rate is changed abruptly, a new primary shockwave front is propagated into the reservoir. Smooth flow rate drift in the range of +10% is desirable.

Observation of a cone of influence

A unique experimental opportunity presented itself in 1987 to observe the

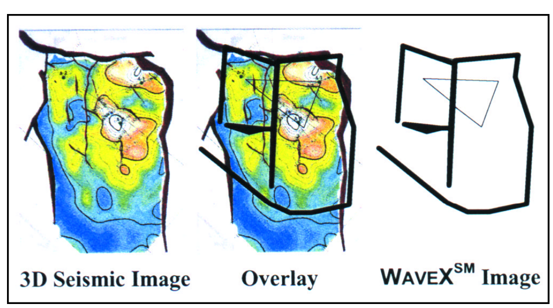

Figure 3. Seismic confirmation example.

growth of a cone of influence from the vantage point of the wellbore of the producing well and two offset wells at 2,000ft and 4,000ft distance. The data plot in Figure 1 depicts the pressure response in the static observation well at a distance of 2,000ft. The producing well was completed in a 500 md sandstone and flowing dry gas at 17 MMscf/d. The time scale originates at the same time the producing well was opened to flow. The observation well was not affected by the offset producing well for the first 28 hours of flow. The double image plot is due to a thermistor cycling between temperature outputs by 0.1ºF. The pressure response begins, not asymptotically as we expect from traditional diffusion theory assumptions, but as a step pressure drop followed by a small half sine wave dynamic. Several pressure step discontinuities were followed by abrupt changes in the semilog slope. Two different wells, two different gauges, very smooth and constant flow, plus a long delay in pressure communication through an extremely permeable reservoir result in the same pattern of pressure anomalies. A third pressure gauge used in a surface readout mode on wireline was placed in a third well 4,000ft from the producer. The surface readout electronic pressure gauge recorded no change in pressure for 104 hours after the producer was opened to flow. A similar pressure step event occurred at that time followed by a sustained drawdown.

The plots were printed upon transparency material. The arrows were placed to note the small step anomalies in the data. The next step is to overlay the two transparencies and scan the resulting overlay.

The propagation of the wave front is solely a function of the hydraulic diffusivity during the midtime region until reservoir closure. As the cone of influence and its bounding shockwave strike the limit, a secondary region forms within the first to make up the production shortfall caused by the limit. The key to the model is an energy solution to a complex network mass of growing capillaries. Radial momentum stabilizes the cone of influence, resulting in a flow system that begins as pure radial flow and continues during the growth phase as radial flow. The well in this case becomes analogous to a lens gathering and focusing light. This is why the point of contact image or its energy equivalent shape can be reproduced (Figure 2).

Note that the pressure data in the semilog plot of Figure 2 is composed of straight-line segments. These features are generally eliminated from pressure data by functional smoothing, filtering and parsing before history matching to a fixed boundary field diffusion model. In this case, we propose to derive limit-specific information from them.

Figure 3 is a simple overlay of the image with the well positioning triangle. It is used to locate the outline over the seismic image. The image is the result of a different geophysical measurement system. This study was produced as a crosscheck to the 3D seismic image for less than 5 on the dollar, including data acquisition.

Capillary stream tubes are not just theoretical devices but represent the physical structural elements of a producing reservoir that allow us to see much more of the reservoir than is promised by conventional diffusion models. Instead of smoothing the discontinuities from pressure data, it is profitable to look for them and process pressure data directly for the information contained therein. Limit-by-limit confirmation from a constant rate flow test offers an independent means for confirming geologic maps. Systematic analysis of several well tests can lead in some cases to blind energy maps. ■