Laboratory Experiments on Pressure Pulse Flow Enhancement in Porous Media[1]

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ABSTRACT

High-amplitude pressure pulsing or mechanical excitation of a saturated porous medium under a pressure gradient increases the flow rate of the liquid along the direction of the flow gradient. Experiments show that this occurs for single-phase liquid systems and two-phase liquid systems (e.g. water-wet, paraffin oil mobile phase) under various conditions and system parameters. The presence of free gas in the system leads to a delay of the effect because the excitation energy is dissipated in compressing the gas.

Experiments have been performed in a wide range of configurations (cylindrical cells and flat plate simulators), grain sizes (30 to 2000 microns), viscosities (1 to ~10,600 cP), and flow factors (e.g. with and without sand flow). Mobile phase flow rate increases of from 30% to over a thousand percent (in the case of the most viscous oils) were measured. These beneficial flow rate effects took place in sand packs without saturation changes, without fabric changes, and under conditions of constant external head. They cannot be rationalized within Darcy theory, as this theory contains no inertial terms. A new theory has been developed.

The flow enhancement effect requires large strains; seismic amplitude strains are inadequate. The nature of excitation is important: high amplitude non-seismic pulses are best. This is most easily achieved in the laboratory and in the field by pressure pulsing, as opposed to other excitation methods.

One of the most interesting series of experiments was related to physical (visual and quantitative) demonstrations that viscous fingering instabilities can be suppressed by pulsing applied to the less viscous invading phase. These results have important implications in the execution of water floods in the field, and can lead to methods of converting old water floods to stabilized front floods.

BASIC FLOW ENHANCEMENT PRINCIPLES

Before our experimental activity is defined and results described, it is best to explain why results do not fall within the “conventional” view of porous media mechanics. What is being done during system pulsing is not radical, but currently accepted poromechanics models cannot correctly account for such dynamic effects. A better theory was developed well before the experiments, and it helped guide the testing program. This theory will now be qualitatively described.

Scientists and engineers working in fluid flow have been taught that the quasi-static Darcy flow paradigm ($q \quad \partial p/\partial \ell$), where gradient is a macroscopically defined quantity ($\partial p/\partial \ell = (p_1-p_2)/\ell$), is a sufficient theory for porous media flow over a wide range of conditions. Perhaps some inability to correctly predict flow rates or dispersion behavior in clays, shales or fractured media is admitted, but otherwise Darcy theory is accepted uncritically.

Similarly, geophysicists working with porous media wave mechanics have been taught that Biot-Gassmann theory is sufficient to describe porous media wave propagation, given a wavelength much greater than the particle size. Neither of these “fundamental” theories is complete, although each may be sufficient for practical purposes under certain restrictive conditions.

Darcy theory is a quasi-static theory, and contains no inertial terms. Thus, when liquid or solid phase accelerations are important with respect to the system flow velocity, one may expect effects that cannot be quantitatively explained. This does not invalidate the Darcy paradigm within the restrictive conditions for which it was stipulated (no inertial effects). It does mean that Darcy theory is incapable of predicting or quantifying the effects that we will report in this article. This is an important point: because Darcy-based flow theories cannot explain our results, it proves that a more complete theory is required.

The Biot-Gassmann theory of wave propagation in porous media is to wave mechanics what Darcy theory is to flow mechanics. Biot-Gassmann theory is based on a set of assumptions that have recently been shown to be inadequate. The two most important flaws are the following:

- Porosity is assumed a constant scalar quantity; and,
- The energy in a porous medium REV can be described by a single-valued function.

It has recently been demonstrated that porosity plays a fundamental thermodynamic role in porous media and must be treated as a thermodynamic state variable. As an example, in attempts to develop physically consistent models of sand production, porosity plays a role similar to that of temperature in metals [1,2]. In sand production, the formation goes from a porosity of 29-32% to a condition of complete liquefaction at porosities >50%, under the influence of gravitational forces and seepage forces. The liquefaction phase transition is akin to temperature-induced melting of metals.

In the Biot-Gassmann development of wave propagation models for porous media, it was assumed that, for a representative elementary volume, the energy state could be expressed by a single functional. This leads to a conundrum that can be demonstrated by a simple example. If a single energy functional is sufficient, there can be only one value and direction of maximum gradient, and if the energy is solely a function of pressure, this means that there can only be one flow direction. However, for decades people have conducted flow experiments where two continuous immiscible fluid phases (e.g. oil and gas) are induced to flow in opposite directions or at 90º. This implies that a single energy functional is insufficient. Indeed, recent work has shown that if N continuous phases exist, N energy functionals (linked together by the laws of physics and properly scaled) are required[2,3]. For example, in a sand-oil-water system, it is theoretically possible that the three phases can be moving relative to one another in three different directions.

Clearly, Darcy theory does not include inertial effects; for example, it is known to be inapplicable at flows involving turbulence[4], where internal energy dissipation from inertial effects are important. During the large amplitude excitation applied to the cells in our experiments, inertial effects, sudden acceleration and deceleration of the pore fluid, dominate the flow regime. To overcome this limitation of Darcy flow theory, it is insufficient to introduce empirical factors: a new flow theory including inertial effects must be formulated at the correct scale from fundamental physical principles.

A new model of wave propagation in porous media was developed to overcome limitations associated with the restrictive assumptions in the Biot-Gassmann theory. The de la Cruz and Spanos model[2,3] utilizes volume averaging in conjunction with physical arguments to construct a set of macroscopic continuum equations that more completely describes wave propagation in a fluid-filled porous medium. This model includes porosity as a dynamic variable that plays a fundamental role in both the thermomechanics and thermodynamics of the porous medium. Also, the model includes explicit thermomechanical coupling; that is, first-order heat generation from compression and expansion of the phases due to external heating and cooling or due to pressure changes. Incidentally, this latter aspect also accounts for well-known wave attenuation behavior in a natural way, without empirical attenuation relationships for which parameters must be evaluated for each specific case.

This theory is developed by imposing the microscopic boundary conditions of no slip, continuity of stress, conservation of momentum transfer and continuity of heat flux to the following equations:

- Equations of motion for a fluid;
- Equation of motion for an elastic solid;
- Continuity equation for a fluid;
- Continuity equation for a solid;
- The solid heat equation; and,
- The fluid heat equation.

It is assumed that the porous medium is composed of pores of random size and orientation, but macroscopically homogeneous and isotropic, enabling the use of volume averaging principles for specific parameters. As a preliminary solution, assuming a plane-wave, new dispersion relations for S and P waves have been constructed. This resulted in four P waves and two S waves, whose phase velocities and attenuation are frequency dependent.

The resulting model consists of coupled, first order macroscopic equations which describe wave propagation in porous media saturated with a single viscous compressible fluid. These equations have been derived and published elsewhere[2,3,5], and will not be repeated here. The basic characteristics of the model include inertial mass coupling between the phases, porosity as a variable, energy dissipation because of phase compression, and rigorous incorporation of the dilational behavior of all phases.

One important aspect of the new wave propagation theory is that it predicts the existence of a non-seismic porosity-pressure diffusional wave that is symbiotically coupled to a quasi-static porosity diffusion process[1] and travels at velocities on the order of 5-150 m/s in porous media. This wave is not predicted by Biot-Gassmann theory. The role of the porosity diffusion wave in the mechanics of pressure pulsing in the laboratory and the field is paramount: it is the porosity-pressure diffusion wave that leads to the flow enhancement.

The porosity diffusion wave disperses geometrically just as any other wave, therefore, as it propagates from the source, its magnitude drops. However, in many cases, particularly those involving irreversible deformations such as compaction (overburden downward movement), energy can be systematically extracted from the gravitational stress field. This is an important aspect: suitable high-amplitude pressure pulsing can trigger dilation and liquefaction; this process is dominated by the overburden stresses and yield (shearing) processes arising from gravitational and flow forces that also feed energy into the porosity diffusion wave propagation process. Indeed, if the wave can continue to extract energy from the surroundings, it can propagate with far less attenuation than expected from geometrical spreading.

The existence and characteristics of the porosity diffusion wave has been demonstrated, measured in the laboratory (velocity ~ 8.0 m/s in a 36% porosity oil saturated sand pack at <0.5 MPa confining stress), and is considered to be critical to the flow enhancement phenomena we observe. The porosity diffusion wave also appears to be important in earthquake mechanics as a mechanism for the triggering of more remote earthquakes in critically stressed regions through an increase in pore pressure arising from a large perturbation.[1]

EXPERIMENTAL APPARATUS[i]

Two types of flow cell are used in the physical laboratory tests, cylindrical and rectangular. The cylindrical cells are as small as 70 mm φ × 150 mm long and as large as 150 mm φ × 1000 mm long (e.g. Figure 1). In these cells, sand is poured in, densified using vibrodensification, and sealed. In some cells, a 1 MPa axial stress is applied to the dense sand pack through a piston. Cells are equipped with lateral orifices for installation of pressure transducers or other devices such as accelerometers or geophones. The cells that are not stressed can be inclined at any angle.

Rectangular flow cells are also used for pressure pulse tests (Figure 2). These are parallel plates (0.15 and 0.75 m^2), of glass 20-30 mm apart that are placed vertically and filled with sand. Once filled, the end platens that control the in-plane flow conditions are replaced, so that all the sand in the model is rigidly held in place. As with the cylindrical models, the rectangular cells can be used in any orientation, so that flow in the cell is "downhill" or "uphill", depending on the goals of the test.

The flow boundary conditions on the cells are straightforward. All walls are impermeable (no flow), entry regions in the cylindrical cells are generally small so that the majority of the flow is one-dimensional along the axis of the cylinder, and convergent flow to the exit orifice is allowed for tests where sand is allowed to flow. Coarse-grained sand or filter stones of high permeability are used at flow ends when a fine-grained sand medium is used in the cell.

Sand can be restrained or allowed to move under the large seepage forces that develop near the exit orifice. (However, in all tests, whether restrained or allowed to exit, sand is initially packed as densely as possible using vibrodensification.) Tests with sand flow were to examine flow enhancement effects in a conscious attempt to simulate the behavior of a perforation in a CHOP well[6]. The exit seepage force is proportional to the area of the orifice and the local exit pressure gradient, which is large because of the hemispherically convergent flow: $\mathbf{F} \quad A \quad \partial p/\partial \ell \quad 1/r^2$. If sand is to be allowed to flow, a sufficiently large exit orifice is used ($d > 10D_{50}$) so that sand arching does not develop to prevent sand efflux.

A commercial data acquisition system is used to take measurements from the pore pressure transducers used in the various cells. The rectangular cells can be photographed under back-lit conditions to give some idea of frontal displacement efficiency, depending on liquid types. Flow rates are generally quite modest and tests seldom last more than a few minutes to perhaps an hour or two for the most viscous oils (10,600 cP), therefore rates are measured using simple graduated cylinders. The pressure drop (Δp) across the entire apparatus is maintained by a large-volume reservoir suspended at a fixed height above the end of the exit line: the height difference is the head, $\Delta p]_{total} = \rho \mathbf{g} \Delta h$, and the large volume reservoir means that $\Delta p]_{total}$ remains constant throughout the test.

Excitation by three different methods was originally tried. A portable radio earphone was stripped, sealed in latex, immersed in the sand pack during densification, and excited using an oscilloscope at frequencies of 30-60 Hz. Very little flow enhancement was observed, and this method was abandoned because both the physical theory and the laboratory results indicated that it is not a viable flow enhancement strategy.

The second method used an impact on the exterior of the cell with a rubber mallet. When a small steel hammer was being used, the flow enhancement effect was negligible to small (0-15%). When the impactor was changed to a rubber mallet with roughly the same total impact energy, much larger flow rate increases were observed. This difference can be attributed to the frequency content of the impact: the steel-to-plastic impact was dominated by high frequencies, whereas the rubber mallet has all of its energy concentrated in the low frequency range that appears to be critical for this flow enhancement process. Figure 3 is a schematic (qualitative) sketch of the frequency content of different excitation approaches.

Blows applied to the exterior of the apparatus are still occasionally used, but mainly for demonstration purposes to show that full solid-liquid coupling takes place in a porous

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[i] Pressure pulsing and its applications are subjects of a series of International Patent Applications and Patents Pending.

medium. Blows also clearly demonstrate that the specific location of the impact has an effect, but any impact seems to increase flow rate. A problem with using exterior blows applied to a cell is that the exterior of the cell is made of Lucite™, which has compressional and shear wave velocities much higher than the enclosed sand pack. Instead of high efficiency of conversion of the impact to porosity diffusion waves in the sand, most of the energy simply was channeled through the dense exterior, and little energy leaked into the flow system, leading to flow enhancements far less than those using pressure pulsing.

Pressure pulsing was adopted as the preferred excitation mode, and as it turns out, pressure pulsing is far easier to implement in the field in actual oil wells[5,7]. A sudden manual squeeze or impact with a hammer on the Tygon™ inlet tube just before the inlet port are the favored methods of excitation. This squeeze or impact does not fully close the tube (Figure 4), nor is there any component of a pumping action (i.e. there is no peristaltic effect, as the tube is not closed, nor is there a "milking" action). A high amplitude local pressure impulse dominated by low frequency propagates in both directions from the impact point, but the flow is not restricted at any time during the impact. The impulse enters the porous medium and is converted largely to a porosity diffusion wave that is accompanied by a small pressure change.

Note that because there is no change in the reservoir or exit tube level, the macroscopic Δp across the test cells remains constant while the short-term impulses are applied periodically (0.1-3 Hz) for several minutes or hours. Conventional Darcy theory application would suggest that the non-pumping dynamic excitation might cause pressure waves, but would not affect the flow rates substantially.

TYPICAL TEST PROCEDURES AND RESULTS

Figure 5 shows results from pulsing a coarse-grained ~35% porosity sand pack (k ≈ 5-8 D) where the sand was oil-wet (35 cP oil) at residual (connate) oil content, then saturated with glycerin (μ ≈ 650 cP) as the mobile phase. The test protocol is typical, and was as follows:

- A constant head ($\Delta p]_{cell}$) is established across the cell;
- Flow is allowed to come to its steady-state rate;
- At this point, the head may be changed to another value, to demonstrate Darcy's law is valid for the sand pack;
- After a steady-state period, the sand pack is excited by pressure pulsing near the inlet port, using the method shown in Fig 4, every 1.5-2 s, typically for 3-7 minutes;
- Pulsing is stopped for a similar interval, started again, and a number of cycles are carried out, followed by a quiet period without excitation;
- After this experiment is terminated, the elevation head (Δp) may be altered, the amplitude, period, or frequency content of the excitation changed, or a different fluid may be introduced to simulate flooding.

The results in Figure 5 indicate a flow rate enhancement of approximately 50%. As with most experiments, there were no saturation changes, the static (Darcy) flow rate always returned to its initial value, the sand pack remained fixed (no fabric changes), the external head was constant, and the fluids remained the same. Thus, changes in phase permeability, hydraulic conductivity, or other factors cannot be invoked to explain the flow enhancement results.

Figure 6 is a test similar to that shown in Figure 5 except that sand was allowed to exit along with the glycerin. Flow rate enhancements approaching 100% were measured in this case. Because sand is moving, the boundary conditions and geometry of the simulation are changing, hence a strict return to the initial flow rate when pulsing is stopped should not occur (i.e. irreversible changes are taking place during flow).

Figure 7 shows the results from monitoring three pressure transducers at different locations along the axis of the cylindrical cell for a test such as that shown in Figure 5. At the transducer just adjacent to the inlet orifice, there is a sharp pressure accumulation taking place with each pulse, and this continues but begins to increase less rapidly until pulsing is stopped, at which point the system almost immediately enters into a classical pressure decay response. The next two transducers, respectively farther from the inlet orifice, showed a slower response and a delayed peak pressure because the "pressure bulb" was diffusing along the cylinder axis, even after excitation ceased. Also, in this test, it was possible to measure the velocity of the porosity diffusion wave, at about 8 m/s in this relatively high porosity and low stress state.

Many tests (over 140 in total) with different fluids and sand packs have led to the following set of conclusions:

- Large flow rate enhancements occur when using large-strain, non-seismic excitation in porous media;
- These flow rate enhancements are because of the dynamic excitation of the fluid phase, increasing the internal pressure and the flow rate.
- Strain levels must be $>10^{-5}$ for the effect to be substantial, far above typical seismic strains ($\sim 10^{-7} – 10^{-10}$);
- The energy source can be a pressure pulse or a strain pulse: because of solid-fluid coupling at the pore scale, conversion occurs, and they are de facto equivalent;
- Impulses dominated by a range of low frequencies are needed for heterogeneous porous media (conversely, single frequency sinusoidal excitation is less effective);
- Viscous fingering instabilities can be substantially modified by pressure pulsing (this was proven by introducing less viscous fluids into a system by pulsing, and noting that instead of channeling, dispersion was favored);
- A detectable porosity diffusion wave is generated by each impulse, and this wave has a velocity in line with predictions of the theory: in the laboratory under low stress (0.5 MPa), velocities of 8-10 m/s were observed;
- A detectable porosity wave (a “tsunami”) diffuses through the system and if the magnitude is large enough it leads to a synergetic internal pressure build-up in the flowing system, changing the pressure gradient from “steady-state” conditions to one where the exit gradients are larger, as well as internal pressures;
- The process is repeatable (reversible) with no changes in phase saturations or in sand pack fabric;
- The process seems relatively more effective in viscous oils, as compared to low-viscosity oils;
- Flow rate enhancement occurs in all liquids, and at all particle sizes tested; and,
- The permeability of the system and the magnitude of the external head dominate the absolute flow rate and post-excitation pressure decay behavior. (In other words, Darcy’s law is perfectly valid in these sand packs for “quasi-static” flow that is not dynamically enhanced.)

MATERIALS TESTED

Different tests in the various different cells have been executed. Following are some of the ranges of materials used, some of the configurations tested, and some conclusions.

Sand pack grain sizes varying from 30 μm to 2000 μm (D_{50}) shows clearly that the geometric property generally referred to as permeability (tautologically defined as $k/\mu = q/(\partial p/\partial \ell)$ in Darcy theory) is a function of grain size. Thus, even though large enhancements during pulsing were observed, the flow rate base line from which these enhancements occurred are certainly in line with general expectations based on grain size.

The rectangular cells were used in various orientations from flat to on-edge, and from “downhill” to “uphill” flow within the cell part of the apparatus. These orientations seemed to have no appreciable effect on flow rate or enhancements. In other words, at the speed of displacement and given that the difference in phase densities (oil-water) was modest, gravitational effects were negligible.

Single phase flow of oil (35 cP paraffin oil; 1400 cP, 1800 cP and 10,600 cP heavy oil) and glycerin (~650 cP) showed that enhancement occurs at all viscosities, but that the amplitude and frequency contents of the pulses need to be tailored to the specific case. Clear evidence of frequency content dependency can be found elsewhere.[8]

Tests in two-phase systems in different configurations using different residual saturation phases (i.e. oil flow in water-wet systems, water or glycerin flow in oil-wet systems) all indicate that flow enhancement is not linked to the presence of two liquid phases, but will occur in all porous systems.

Limited test cases of three-phase fluid systems where one phase is dispersed gas bubbles show that gas delays the effect substantially, and that pulse enhancement becomes more effective once the gas is driven back into solution.

STABILIZATION OF VISCOUS FINGERING

After the flow rate enhancement effect had been well explored, one of the more exciting aspects of the on-going experimental program is demonstrating that viscous fingering instabilities can be controlled through pressure pulsing.

Attempting to displace a viscous oil (>1000 cP) with water under constant pressure invariably leads to early water breakthrough following minimal oil production. (It should be noted that, despite conventional theoretical predictions to the contrary, some Canadian operators are executing profitable water floods in heavy oil. However, these projects have high water/oil ratios and poor total recovery.)

Figure 2 shows the configuration of a typical pressure-pulse water flood experiment in heavy oil using the rectangular flow cell. The experimental protocol is as follows. The cell is filled with quartz sand, densified, water saturated, and slowly displaced with paraffin oil or heavy oil from the field (viscosity from 35 cP up to 10,600 cP dead oil). This leaves the apparatus at a "connate" water saturation, on the order of $S_w \sim 0.10$, and $S_o \sim 0.90$. Note that these are approximately the saturations found in situ in many beds.

In the first experiment, a 1.0 m head of water is applied to one end of the cell without pulsing. Typically, some oil is produced at a slow rate, then water breakthrough occurs (after 10-15 min in heavy oil), and the water cut continues to rise. In a pressure pulse waterflood experiment, an identical set-up is employed, but as soon as the constant head is applied, the inlet tube is impacted approximately once every 1-2 seconds, as with other similar flow enhancement experiments.

Figure 8 shows the flow results for both experiments, superimposed on the same graph. In the dynamic case, pressure pulse excitation was continued for ~38 min. Oil flow began, increased, stabilized, and then flowed with essentially minimal water cut for the full 38 min, and at a rate considerably faster than that for the non-pulsing (but otherwise identical) test. After the end of the experiments, the total water and oil content of the effluent was determined. In the non-pulsing case, 65% of the fluid was water; in the pulsing case, on the order of 10%, and at this point, over 25% of the oil in the apparatus had been displaced. Thus, not only did the fluids flow faster, the oil content remained high, the displacement efficiency was maintained for a long time, and the oil recovery was high. In similar experiments when pulsing was stopped after some time but the head of water remains, the oil continues to flow well, but after a few more minutes, water breakthrough is noted, and the water cut increases until almost 100% water flow is observed after some time. It is worth repeating that the conditions for both experiments were identical, except for the pressure pulsing.

Figure 9 shows results of similar experiments in a 35 cP paraffin oil (note that the entire experiment lasts no more than 6 min, rather than the 40-200 min typical for heavy oil experiments). Also note that the non-pulsing curve, similarly to the one in Figure 8, is almost a perfect exponential, as predicted by first-order linear instability theory (based on non-inertial theory of course), as we would expect. The flow curve for the pulsing case takes a sudden jump upward, and this corresponds to the point where the entire "reservoir" is pressurized by the synergetic effect of the porosity diffusion wave and pressure diffusion processes. (This "jump" is less obvious in more viscous oils, but can be seen as well in Fig 8.) As in the previous experiment, not only was the flow rate dramatically increased, but the oil sweep efficiency was much higher that for the non-pulsing case.

Figure 10 (a,b,c,d) contains photographs of the flat cell at similar times to compare pulsing and no pulsing in the connate paraffin oil case shown in Figure 9. In the pulsing case, the water is dispersed more evenly from the entry port, more evenly displacing the oil from the porous medium. Displacement has also been achieved much more rapidly: at 138 seconds the pulsing displacement process was essentially complete, but a high oil rate was still coming from the pulsing case.

Clearly, high-amplitude, low-frequency pressure pulse excitation suppresses viscous fingering and promotes the more rapid propagation of a more stable displacement front between the fluids of widely differing viscosities. Figure 11 is a schematic representation of the process, where in the pulsing case, the displacement front is characterized by many short fingers, all length-stabilized by the pulsing. Note that these "snapshots" are at the same time, as the flow rate in the pulsing case is much faster.

There are also interesting effects (all positive!) if water flooding is attempted in an oil-wet system, compared to systems with a connate water phase. We will describe these in more detail in forthcoming articles.

We have also explored the effect of pressure pulsing on a flat cell with longitudinal permeability inhomogeneities built in using streaks of different granular materials. Without pulsing, channeling is obvious and rapid, but with aggressive pulsing, the flow front is far more even, and much of the oil from the less permeable streaks can be produced.

These results may seem counter-intuitive in a Darcy flow context.[9] However, a phenomenological law developed in static flow experiments without pressure pulsing, using a theory that does not account for inertial effects nor for porosity as a thermodynamic variable (i.e. the Darcy paradigm), cannot be expected to be valid for the case of pressure pulsing. In this case, the energy put into the system, generating the propagation of porosity diffusion waves, dominates the flow and displacement behavior, suppressing fingering.

DISCUSSION AND CLOSURE

Although there are many effects that need to be quantified and refined, the experimental program showed that flow rate enhancement will always accompany appropriate large strain excitation. Laboratory work shows that the periodicity of impact and the frequency content and amplitude of the pressure pulsing are important aspects. Also, pressure pulsing applied to the water phase of a water flood suppresses the growth of viscous fingers, retarding early water breakthrough and increasing oil sweep efficiency.

In a virgin reservoir that is to be waterflooded, the water should be injected using massive pulses in the injection wells, starting at the beginning of the process and carried out continuously at full volumetric efficiency.[7] In an old reservoir that has full water breakthrough, but much oil in place, the procedure would probably be as follows. First, in the wells to be oil producers, inject oil under aggressive pulsing to shut off the watered-out channels and “push” the water fingers away from the future production well. The time and oil volume required will vary from field to field and from well to well, and the response of the well will be diagnostic. The oil injection will probably be at about 10-20% volumetric efficiency.[7] Second, after a sufficient time, switch the pulsing to the water injection in the waterflood wells. Start off with 10-20% volumetric efficiency while monitoring carefully the response of the oil producing wells and the pressure response of the pulse injection wells. Gradually increase the volumetric efficiency as allowed by the reservoir response. The water flood should now produce much more oil.

We do not yet have a version of the theory that can predict the magnitude of flow rate enhancement for a particular set of boundary conditions and pressure pulse excitation characteristics. However, the general predictions of the theory (existence of a porosity diffusion wave, the flow enhancement effect, the synergetic pressure build-up, viscous fingering stabilization, etc.) are verified. We therefore believe that pressure pulsing is a new production mechanism that can be exploited and engineered to operate at optimum conditions in different reservoirs. Initial field tests bear out these opinions[5,7].

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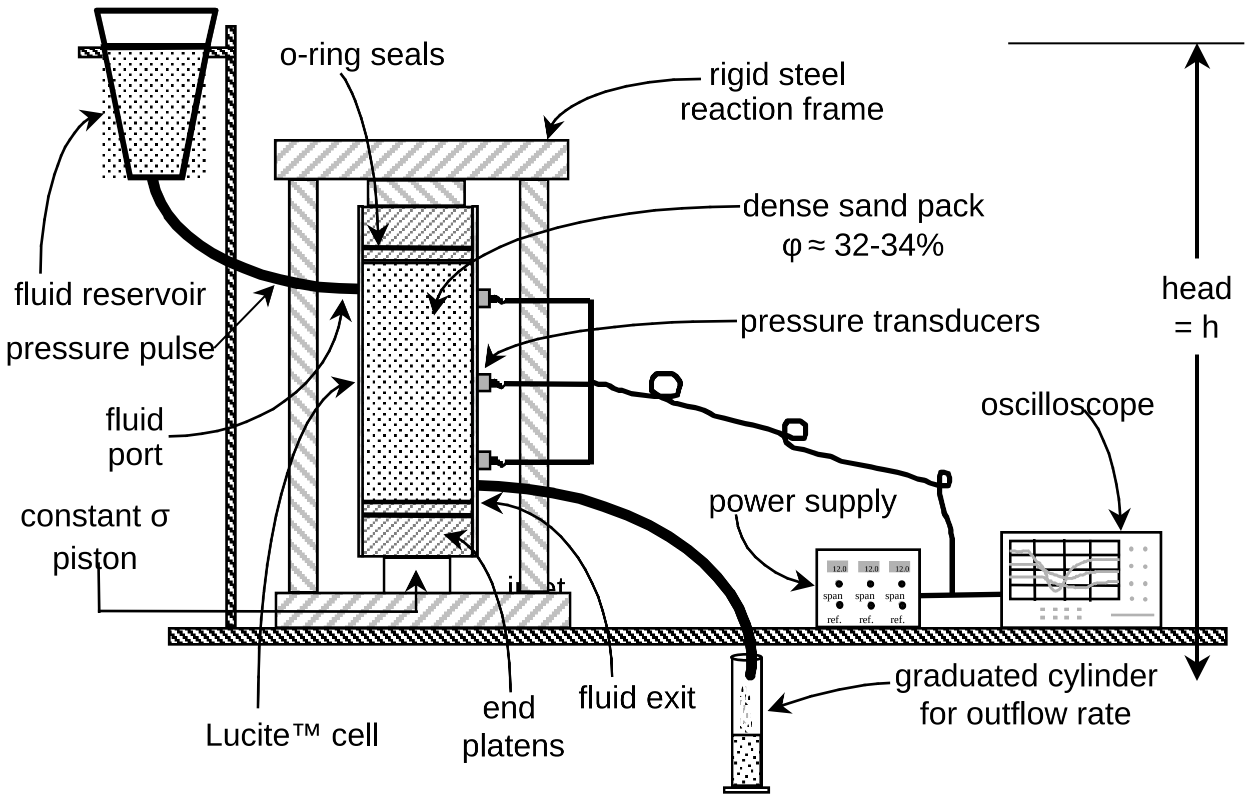


Figure 1: Cylindrical, Stressed Flow Cell and Data Acquisition System

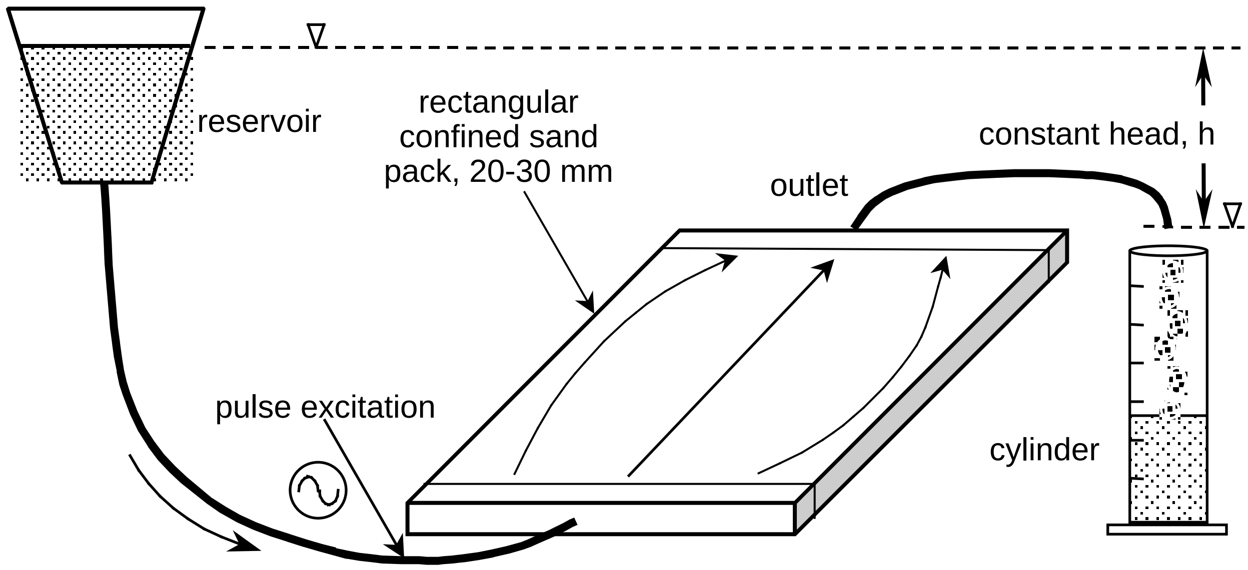


Figure 2: Rectangular Flow Cell Shown in an “Uphill” Position

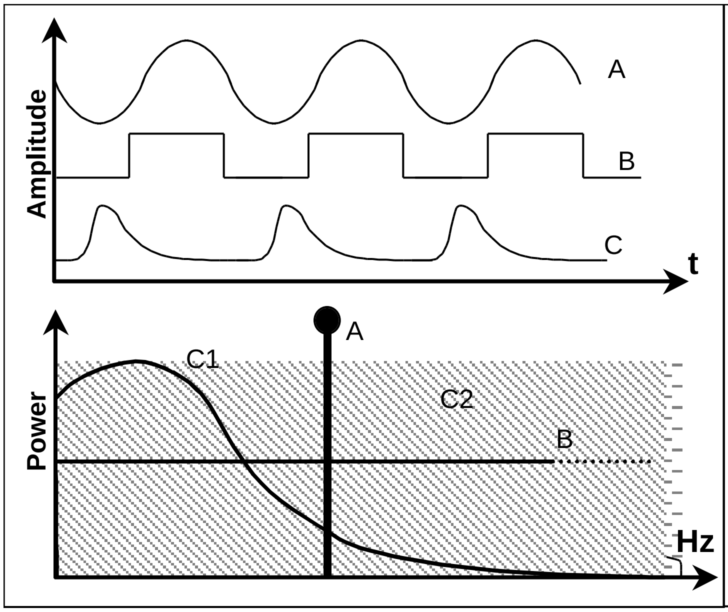


Fig 3: Pulse Frequency-Power Content

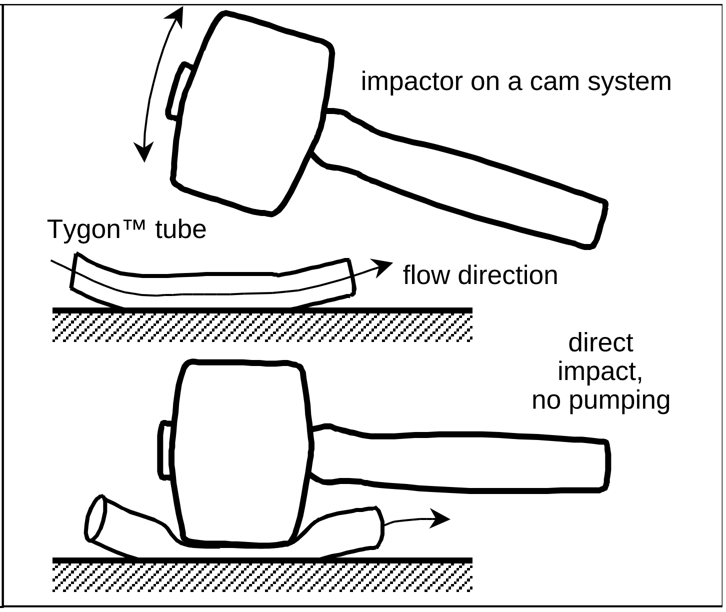


Fig 4: Pressure Pulse Generation Method

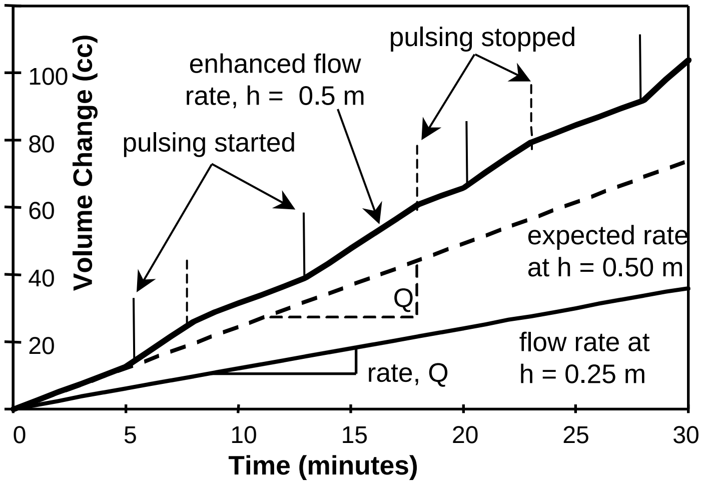


Fig 5: Flow Enhancement, Sand Pack Static (pulsing every1.5-2 s)

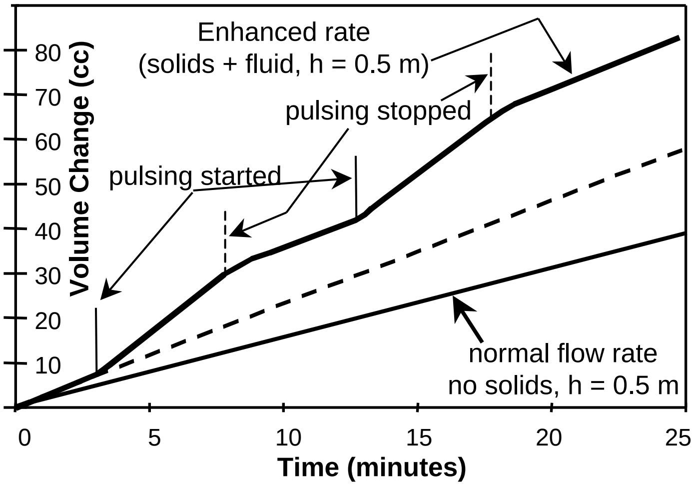


Fig 6: Flow Enhancement with Sand Production (same conditions)

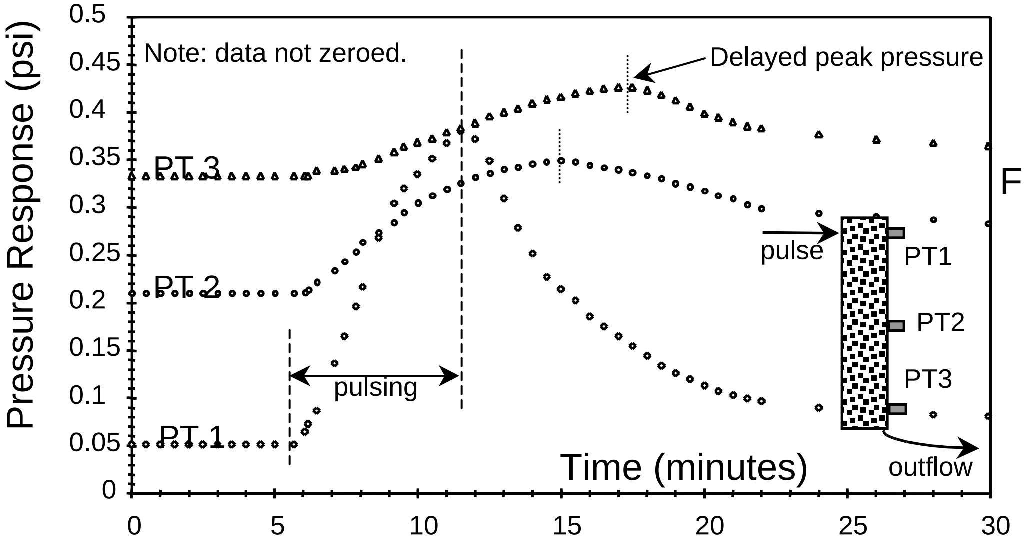


Figure 7: Internal Pressure Response to Pulsing at the Upstream Entry Port (30 cm cylinder cell)

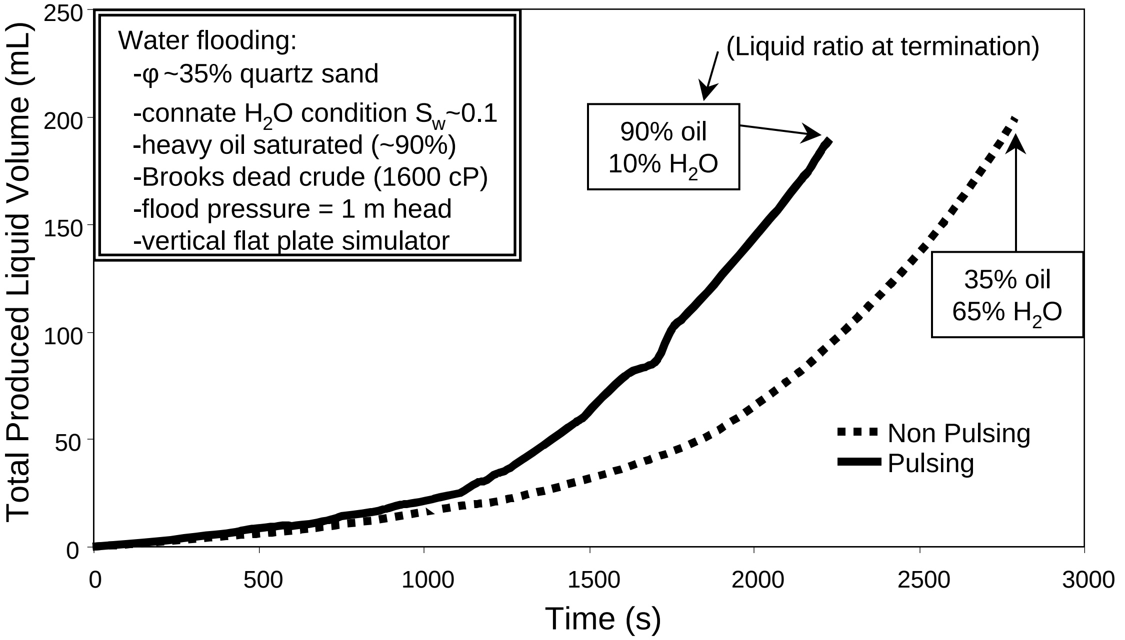


Figure 8: Comparison of Pulsing and no Pulsing, Identical Conditions

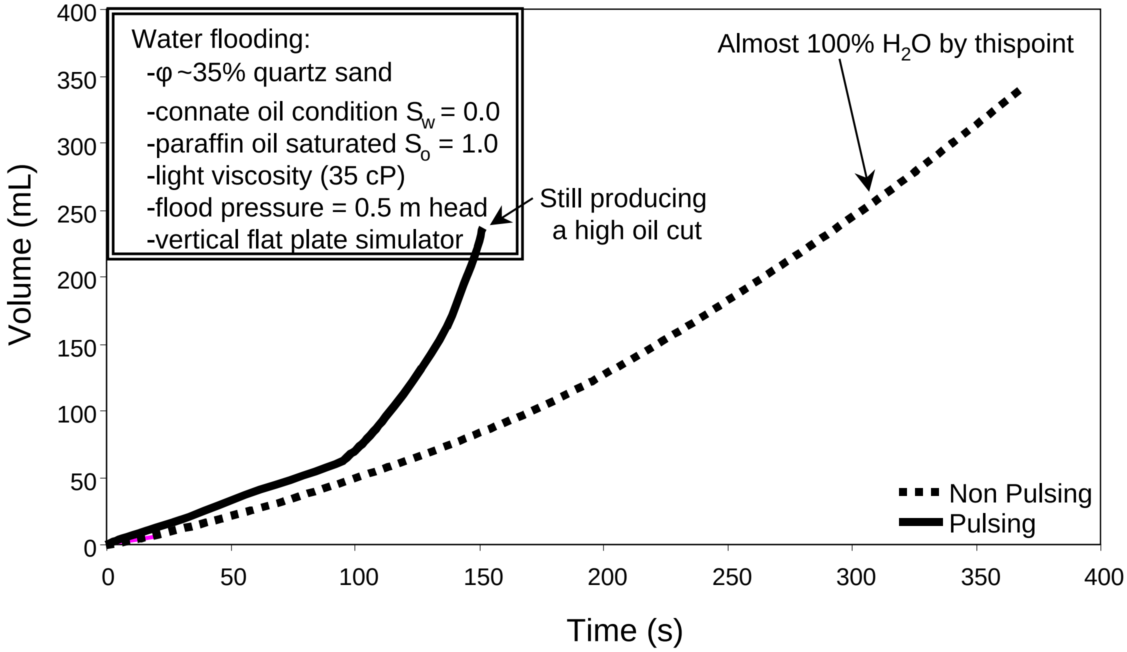
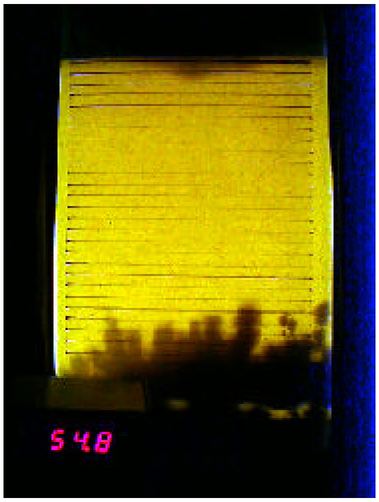


Figure 9: Pulsing and no Pulsing in an Oil-Wet System

Figure 10: Connate Paraffin Oil Case Shown in Fig 9 - Water Flooded
Comparison of Non-Pulsing Viscous Fingering
Versus Pulsing Dispersional Effects and Rates



Time = 54.8 s

Time = 54.9 s

Time = 139.2 s
Non-Pulsing

Time = 138.7 s
Pulsing

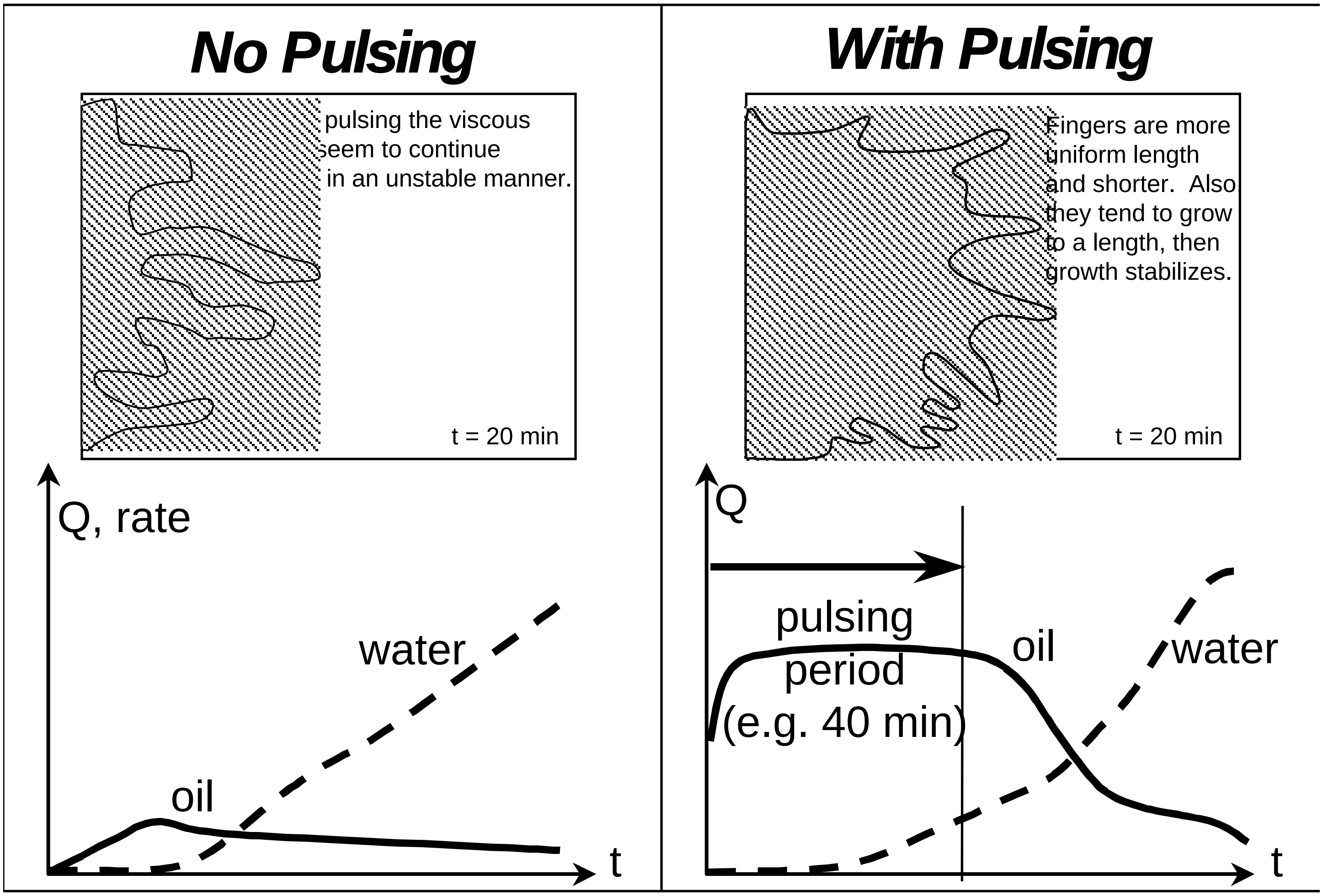


Figure 11: Schematic Representation of the Major Effects Seen in Pulsing and Non-Pulsing tests on Oil-Wet Systems:
-General flow rate is faster with pulsing
-Water breakthrough is slower with pulsing
-Oil cuts remain higher for longer with pulsing
-Oil sweep efficiency is far greater with pulsing
-Viscous finger length is suppressed with pulsing
-Stability of the fingering front is greater with pulsing