FLUID ENHANCEMENT UNDER LIQUID PRESSURE PULSING AT LOW FREQUENCY

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Abstract

It has been found that periodic or continuous excitation of a porous medium under a constant external fluid pressure can lead to a change in the internal pressure distribution. This leads to an enhancement of flow rate by as much as 90% even in the absence of compaction or fabric changes. When excitation is stopped, the enhanced flow rate decays slowly to the previous steady-state flow rate.

Synergetic internal effects associated with the phenomenon of porosity diffusion appear to be responsible for the flow rate increase. It appears that Darcy’s law remains valid; the increase in rate arises because of internal pressure changes caused by the excitation.

Introduction

Finding effective and economic means to enhance oil production in reservoirs has long been a focus in petroleum engineering. Various methods have been developed for oil recovery; each uses new energy or adds additional material into the reservoir to change production conditions. Examples include *in situ* combustion, steam or water injection, or chemical injection.

We have found that pulsing the liquid phase of a saturated porous medium at low frequency will lead to an enhancement in fluid flow rate. This phenomenon is important in reservoir engineering, and may be useful in other applications involving porous media, such as chemical reaction beds, or water resource exploitation.

Laboratory tests in early 1997 demonstrated that pulsing the liquid phase in a porous medium under stress with constant external fluid head leads to enhanced fluid flow rates upwards of 120% [1], [4] and [5]. Experiments were carried out on dense sand packs under constant stress with no sand efflux, as well as on sand packs where sand efflux through an orifice was permitted. Those tests showed that mechanically tapping the outside of the samples or generating low frequency acoustic waves inside the samples also enhance fluid flow rates. To achieve further understanding of this phenomenon, further laboratory tests are being undertaken.

On-going laboratory testing confirms that pulsing the liquid phase enhances fluid flow rates up to 80 %. We also find a “**transient after-effect**” following pressure pulsing: a period where the induced internal excess pressures dissipate as steady-state flow is approached.

Qualitative Theoretical Discussion

Earthquakes or explosions generate strong perturbations and produce irreversible changes in porous media (i.e. fracture, dilatancy, and compaction). If a strong perturbation leads to a decrease in porosity, an effective compaction occurs, squeezing an additional amount of fluid from the porous medium (Figure 1). Strong perturbations, like vibration, may also displace liquid droplets in a multi-phase porous system, aggregating these droplets into a continuous phase, which is then capable of flowing (Figure 2). The phenomenon of enhanced flow was noticed following earthquakes in the 1970′s in Russia [2]. The association of fluid rate enhancement following a strong perturbation is reasonably well understood.

In contrast with strong perturbations, weak perturbations, such as liquid pressure pulsing and mechanical tapping, are of an elastic nature. An elastic perturbation will not produce a residual, irreversible deformation. There should not be permanent porosity or permeability changes after an elastic perturbation. What is the physical mechanism for fluid flow enhancement by a weak elastic perturbation?

Geilikman et al. [3] have put forward the following synergetic process hypothesis: although an elastic excitation does not produce any residual, irreversible deformation, it does cause a periodic perturbation in the porosity of the system through elastic compression and relaxation. In the aftermath of an impulse, a porous medium relaxes to the equilibrium state in a diffusional manner because the relaxation process involves flow of the viscous saturating fluid with respect to the porous skeleton. If another perturbation is applied before the preceding one fully decays then a cumulative, synergetic effect can be achieved. Note that a pressure gradient must exist for this synergism to take effect.

Darcy's law controls fluid flow in a porous medium:

$$q = -\frac{k}{\mu}\rho g \frac{dh}{dL} \qquad (1)$$

Where k is permeability, μ is fluid viscosity, dh/dL is hydraulic gradient, ρ is liquid density, g is the gravitational acceleration.

In a homogenous medium, if there are no changes in porosity or permeability (k is constant), for a particular fluid (μ is constant), then an increase in q will result from an increase of dh/dL. From the "synergetic process" idea, if a liquid pressure is added at a point in a saturated medium, it will take some time for the pressure to viscously dissipate. Therefore, if we pulse the liquid phase frequently to ensure that the next pressure addition takes place before the full decay of the previous pressure pulse, this will build up a high internal gradient of hydraulic head (dh/dL). Figure 3 conceptually shows this idea.

Test Goals and Methodology

Though test results to date are both exciting and encouraging we consider our initial experimentation first order. We continue to modify our experimental approach as well as the scope of test parameters. At present, the following experimental modifications and test parameters are being carried out:

1. Development of a consistent excitation source.
2. The effect of material compressibility.
3. The amplitude and frequency of the excitation source.
4. The grain size of the porous medium.
5. The influence of gas on enhancement.
6. Other parameters identified through discussion and consultation with others.

Test Equipment

An outline of the test equipment [4], [5] is shown in Figure 4. Three pressure transducers are used to measure both the speed and magnitude of the induced pressure wave from a single pulse, or the pressure build-up and dissipation process during prolonged excitation.

Specimen Preparation

Specimens are prepared using quartz sand (Ottawa sand) with specific gravity 2.65. Light paraffin oil is used as the wetting phase. The density of the oil is 0.85 g/cm^3 and the viscosity is 25.5 cp. Figures 4 and 5 illustrate the test system and the specimen assembly procedure. The procedure for preparing the specimen is as follows:

1. The stainless steel test cell is placed upright on a vibrating table.
2. Paraffin oil is poured into the annulus of the cylinder filling about half the volume of the cell.
3. Approximately 3~4 cm of sand is placed into the annulus of the cell. The surface of the oil is above the surface of the sand.
4. The vibrating table is switched on and the test cell containing the oil/sand mixture is allowed to vibrate for 10 minutes.
5. Another 3~4 cm of sand is placed into the cell and, if necessary, more paraffin oil.
6. Step four is repeated until the specimen reaches the required height.
7. The porosity of the vibrodensified specimen is calculated.

In general, samples prepared using vibrodensification achieve a porosity of about 32 to 34%. This is a typical value for a dense sand pack prepared in the laboratory. Once the sand pack is prepared the remaining components of the cell are assembled, and paraffin oil is allowed to flow under a low hydraulic head (about 0.5 m) through the bottom port of the cell. Though the specimen is most likely saturated from the preparation stage the placement of a low hydraulic head ensures saturation and elimination of any entrained air bubbles. The low hydraulic head is maintained for a period of several days prior to test initiation.

Test Procedure

The test procedure followed these steps:

1. The test cell containing the vibrodensified specimen is secured in a loading frame and the cell is connected using flexible tubing to fluid reservoirs containing glycerin oil on the upstream inlet and paraffin oil on the downstream outlet.
2. The flow lines are opened to initiate displacement of the paraffin oil with glycerin oil under a maximum hydraulic head of 1.0 m (in many instances the displacement phase uses a hydraulic head of 0.5 m) to create a paraffin wet matrix with glycerin oil as the mobile phase.
3. A vertical stress of 1.0 MPa is applied to the specimen with measurements of axial displacement (Δh) being recorded by an LVDT.
4. Using Δh, a new specimen height is determined and porosity recalculated to obtain the specimen porosity used during subsequent flow calculations.
5. When all "free" paraffin oil has been displaced with glycerin oil measurements of steady-state flow are made at various hydraulic heads to establish baseline flow characteristics for the test specimen.
6. A pressure pulse is induced by squeezing the flexible inlet tubing at a rate of approximately 1 Hz or the exterior of the test cell is tapped using a rubber mallet (creating a strain pulse) at a rate of approximately 1 Hz.
7. Measurements of internal pressure changes with time and fluid outflow rate are recorded (it is important to note that the hydraulic head across the specimen remains constant throughout the test).
8. Steps 6 and 7 are repeated for various time duration's to observe the affects of single, periodic, or continuous excitation.

Outflow Rate under Pressure Pulsing

Test 1, Figure 6, was conducted by gently pulsing the flexible fluid line manually at a frequency of 1 Hz. Again, no effective increase in external fluid pressure was placed on the specimen because the hydraulic head remained constant. Figure 6 shows that pressure pulsing enhanced fluid flow rate by 82%, compared with the steady-state flow.

The sand from Sample 1 was recompacted with a small amount of additional sand using the procedures outlined above to make Sample 2. Glycerin oil was allowed to displace the paraffin oil and complete glycerin oil saturation was achieved after four days. Thus, an oil-wet system was created with glycerin oil as the mobile phase. The porosity of Sample 2 was calculated to be 34%.

With Sample 2, two tests (test 2 and test 3) were conducted to examine the relationship between pressure pulsing and the outflow rate. Test parameters and results are shown in Figures 7 and 8 repectively. These two results show fluid flow rate increases during pressure pulsing. The comparisons of steady state outflow and pressure excitation outflow are shown in Figures 9 and 10. Increases in flow rates of 60% and 65% were achieved.

In Figures 7 and 8, it is apparent that the fluid flow rate immediately after the excitation ceased is higher than the baseline steady-state flow rate. To get quantitative information about this phenomenon, we compared the steady-state outflow rate and the outflow rate at the cessation of pulsing. Results are shown in Figures 11 and 12. The enhanced flow rate immediately after pulsing is about 30% and 38% compared to steady-state flow; we call this temporary phenomenon a "**transient after-effect**". It is related to the decay of internal pressure.

Monitoring of test 2 lasted for approximately five hours and for test 3 approximately six hours. For the two tests on Sample 2, we compared the steady-state flow before and after the pulsing. This interesting comparison is shown in Figures 13 and 14. Clearly there is no change in steady-state flow rate before and after pulsing. These comparisons support the argument that a weak perturbation does not produce irreversible deformation. If there were an irreversible deformation then the porosity would be changed which would lead to a detectable permeability change. If the permeability had been changed, according to Darcy′s law, the outflow rate would also have changed. This demonstrates that the enhancement of flow rate is the result of an elastic (reversible) cyclic strain perturbation.

Examination of Pressure Build-up / Decay

To examine internal pressure changes, the pressure variation resulting from one pulsing cycle was measured on Sample 1. The result, shown in Figure 15, provides some valuable information.

1. Pressure increase and decay are time dependent.
2. The process of pressure decay is longer than the process of pressure increase.
3. It is possible to add the next pressure pulse before the full decay of the previous pressure pulse.

Following this test, three pressure build-up and decay tests were conducted on Sample 2. Results are presented in Figures 16 and 17. In Figure 16, the slope of the decay curve is lower than the gradient of the pulsing curve. As seen in Figure 17, approximately 35 minutes passed before the entire system pressure equilibrated to original background levels. These results support the hypothesis of "pressure build-up" / decay concept.

Discussion

Mechanisms for this phenomenon For a porous medium consisting of an elastic matrix fully saturated with viscous fluid, Geilikman et al. [3] showed that a porosity diffusion wave propagates from a seismic source. This process causes a travelling pulse of pressure associated with the spreading front of porosity, and results in variations of fluid pressure [6]. Through the use of volume averaging and basic arguments, de la Cruz and Spanos [7], [8] proposed a system of equations for low-frequency seismic waves propagating in homogeneous porous media. Recently, Spanos et al. [9] include frictional sliding at grain contacts and put forward a theory which predicts that a pressure pulse associated with the porosity diffusion wave may propagate through an unconsolidated medium at a speed of 10-100 m/s.

From the above theory, we suggest that pressure pulse excitation generates a series of porosity diffusion waves in a homogeneous elastic medium, giving rise to pressure variations. The increase in internal pressure leads to an enhancement in fluid production rate.

During laboratory testing, pressure pulse excitation was generated by hand, and the magnitude of each pulse was small. However, from these tests we found that the rate of increase in fluid flow is related to the overall pressure magnitude. Thus, the mechanisms for fluid flow rate enhancement must include both porosity diffusion wave propagation and internal pressure increase.

As this phenomenon may relate to the compressibility of the porous medium, tests are now being conducted to quantify compressibility effects. Materials being tested include glass beads, stainless steel balls, lead balls, and polyurethane beads.

Weak perturbations Weak perturbations can be generated by different methods including, liquid pressure pulsing, mechanical tapping on the exterior wall of the test cell, or micro-vibration inside the sample.

In experiments carried out in early 1997, a small acoustic emitter was embedded near the exit port, and excited at 20–60 Hz during flow. Increases in flow rate were observed, but these were small (0–25%) compared to pressure pulse excitation.

At present, we believe that the periodic excitation applied by pulsing the inlet tube is the most effective method of excitation because of the larger amplitudes and because all (or almost all) of the energy is transmitted directly to the specimen. Internal micro-vibrations using the small acoustic emitter are amplitude-limited, and therefore give much less energy of excitation to the system. Mechanical tapping of the test cell externally can give a large energy impulse, but the great majority of this strain energy may remain outside the porous medium because the containers and frame are stiff, whereas the specimen has a much lower modulus (about 2 orders of magnitude. Nevertheless, in the systems tested to date, mechanical tapping does result in enhanced fluid flow rates.

Pressure build-up During the tests, it was noted that the nature of the internal pressure increase depends on pulse magnitude and the distance from the impulse source. Table 1 shows the pressure increase in different situations. From this data two conclusions can be obtained.

1. The rate of pressure increase depends on the magnitude of the pulse source (amplitude).
2. The attenuation of the impulse over distance through the sample affects the pressure increase. This can be seen from results given for Test 3 in Table 1. Pressure transducer 1, closest to the pulse source, increased by 2.477 kPa whereas pressure transducer 2, furthest from the pulse source, only showed a 0.564 kPa pressure increase.

Geilikman et al. [3] give an equation that states that if the point source of the impulse is distant, R is large, and the enhancement is accordingly much less. This implies that the closer the impulse to the entry area (the perforation openings), other things being equal, the greater the enhancement effect. We continue to examine the effects of pulse attenuation and spatial distribution in stressed granular media.

Frequency Pulse frequency used during testing was generally 1 Hz (1 pulse/sec). To explore frequency effects, a test at three different frequencies – 1Hz, 0.5Hz, 0.25Hz was performed (Figure 18). Results demonstrated that pulsing at 0.25Hz (1 pulse/4sec) generated the highest increase in fluid flow rate. This may be related to the shape of the pulse suggesting that each pulse will take a certain time to generate an effect. We believe there is an optimum excitation frequency and we continue to explore this issue. Though hand pulsing has generated quality results it is not an optimum method, and the next series of tests will use an excitation source that is more consistent and controllable.

Viscosity Viscosity has an influence on the fluid flow rate. Table 2 shows that less viscous fluids appeared yield higher increases in fluid flow rates than more viscous fluids, but results are not conclusive. Because many factors can affect the fluid flow rates, it is too early to make an accurate prediction on the effects of porosity and viscosity variations and how they scale to excitation characteristics. These issues are the focus of current experimentation.

Pressure and outflow reaction. The reaction of pressure and outflow rate in the tests occurred soon after pressure excitation started, and the pressure decreased rapidly after the pulsing stopped. An outflow increase was maintained for a period after the pulsing stopped, which we call a transient "**after-effect**". This "after-effect" is due to the internal liquid pressure that takes time to fully dissipate.

Clearly, this "after-effect" has a characteristic time that is related to the permeability and the viscosity, and it appears to follow a typical decay pattern associated with diffusion of pressure. Again, one should note that the external head on the specimen was never changed during these tests, and the decay is only of the excess pressure generated by the cumulative effect of the pulsing. Figure 19 attempts to show the concept.

In Figure 17, we notice that the time for pressure decay in transducer 2 is longer than that in transducer 1. This is also dependent on the location, as suggested in Figure 19, and is related to the external diffusion of the induced excess pressure.

Conclusions

1. Liquid pressure pulsing can enhance liquid production, even in the absence of a change in the external head.
2. A synergetic effect is achieved leading to internal pressure build-up by consecutive pressure pulses.
3. Darcy's law appears to hold true at the pore scale of this phenomenon.
4. Fluid flow rate enhancement is not related to compaction or fabric changes or changes in hydraulic head (steady-state rates before and after were identical).
5. A preliminary theoretical analysis shows that elastic perturbations of sufficient strain amplitude predict a flow rate enhancement, providing that a gradient exists across the medium.
6. The porosity diffusion mechanism appears to be the mechanism for the transmission of the energy into the system.

Acknowledgments

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References:

1. M. B. Dusseault, 1997, Enhancement of Fluid Flow Using Large-Strain Excitation. A*nnual Meeting Abstracts,* Porous Media Research Institute, University of Waterloo, Canada.
2. V. N. Nikolayevsky, 1988, Mechanism And Dominant Frequencies of Vibrational Enhancement of Yield of Oil Pools. *Doklady Akademii Nauk SSSR,1989,* Vol. 307, No.3, pp. 570.
3. M. B. Geilikman, B. Davidson, M.B.Dusseault, K.Hayes, and T.J.T.Spanos, 1997, Estimation of Cumulative (Dynamic) Enhancement of Fluid Production from a Pulse Series. *Internal Document.* Porous Media Research Institute, University of Waterloo, Waterloo, Ontario, Canada.
4. B. C. Davidson, M. B. Dusseault, M. B. Geilikman, K.Hayes, and T.J.T.Spanos. 1997, Dynamic Enhancement of Fluid Flow Rate Using Pressure and Strain Pulsing. *Patent Application, March 1997.* PE-TECH Inc., Cambridge, Ontario, Canada.
5. B. C. Davidson, 1997, Equipment Design and Test Procedures for Laboratory-scale Examination of the Dynamic Enhancement Process. *Internal Document.* Subterranean Technologies Incorporated, Cambridge, Ontario, Canada.
6. M. B. Geilikman, T.J.T.Spanos and E.Nyland, Porosity Diffusion in Fluid-Saturated Media. T*ectonophysics,* 217 (1993) 111-115, Elsevier Science Publishers B. V., Amsterdam.
7.] de la Cruz., and T. J. T. Spanos, 1985, Seismic Wave Propagation in a Porous Medium. *Geophysics,* 50 (10), pp. 1556-1565.
8. de la Cruz, V., and T. J. T. Spanos, 1989. Thermomechanical Coupling during Seismic Wave Propagation in a Porous Medium. *I. Geophys. Res.,* 94, pp. 637-642.
9. T. J. T. Spanos, M. B. Geilikman, M. B. Dusseault, 1997, *Untitled Manuscript*. Porous Media Research Institute, University of Waterloo, Canada.

Table 1. Comparison of Pressure Build-up

Pulse Method	Effective Stress (kPa)	Transducer No	Sample No	Head m	Frequency Hz	Pulsing Time (min)	Pressure Build-up kPa	Build-up Rate kPa/min
A	10	T1	2(test 2)	1	1	15	3.816	0.25
B	500	T1	2(test 3)	1	1	15	2.477	0.17
C	500	T2	2(test 3)	1	1	15	0.564	0.038

Table 2. Comparison of Viscosity

Sample	Pressure kPa	Head m	Porosity (%)	Viscosity (cp)	Flow Increase (%)	Frequency Time/sec
1	0	0.6	34.2	25.8	82	1
2	10	1	34	934	60	1

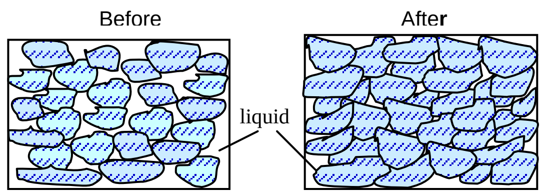

Figure 1 Compression Effect

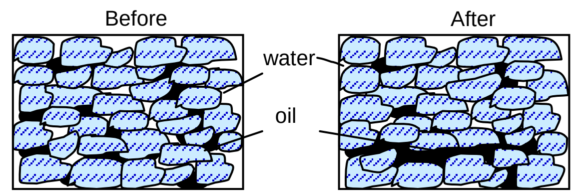

Figure 2 Vibrational Effect

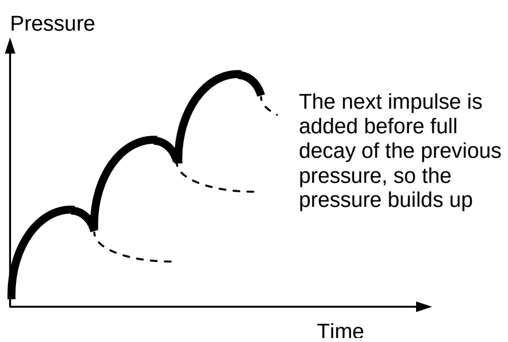

Figure 3 Concept of Local Pressure Build- up by a Synergetic Process

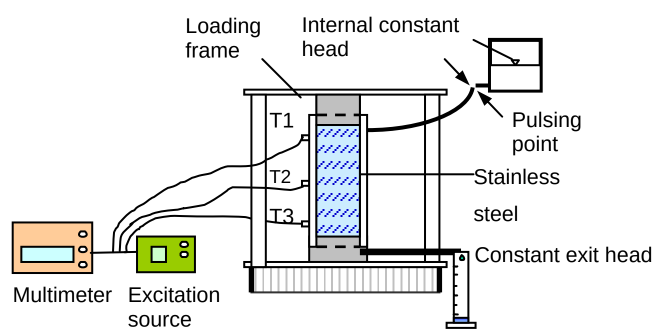

Figure 4 Pressure Pulse Test Apparatus

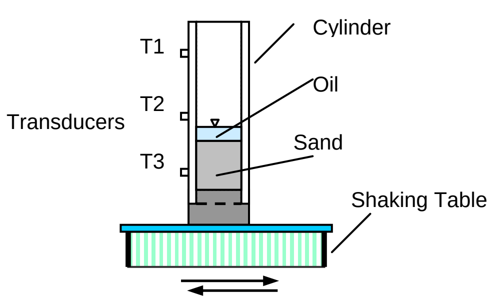

Figure 5 Sample Creation

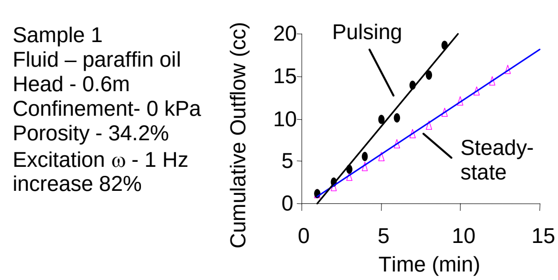

Figure 6 Pulsing Test #1

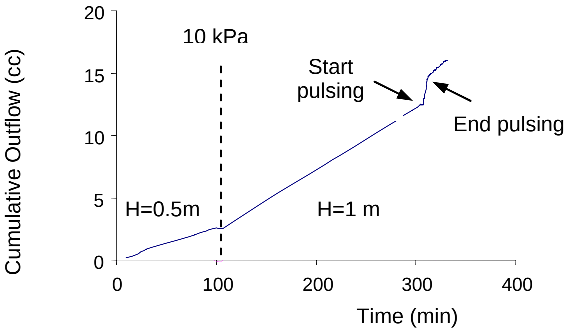

Figure 7 Test 2 – Pulsing Test

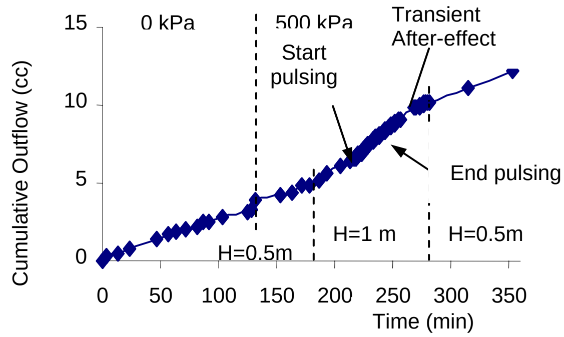

Figure 8 Test 3 – Pulsing Test

Sample 2
Fluid –glycerin
Head – 1 m
Confinement-
0 kPa
Porosity- 34 %
Excitation
ω - 1 Hz
Increase 60%

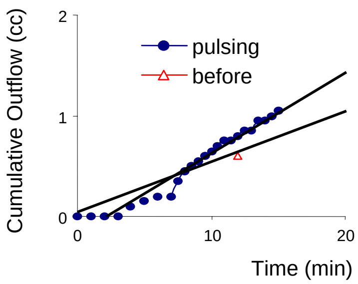

Figure 9 Outflow Comparison

Sample 2
Fluid- glycerin
Head – 1m
Confinement-
500 kpa
Porosity-34 %
Excitation
ω - 1 Hz
Increase 65%

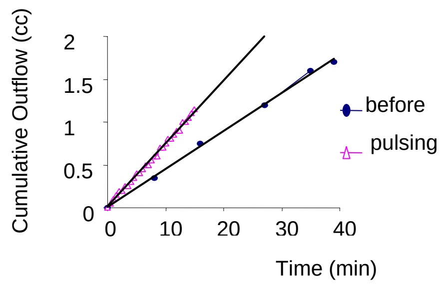

Figure 10 Outflow Comparison

Sample 2
Fluid - glycerin
Head - 1m
Confinement
0 kPa
Porosity 34%
Excitation
ω- 1Hz
After-effect
38%

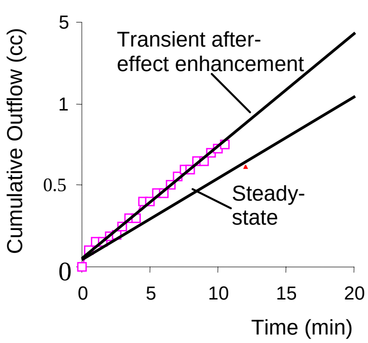

Figure 11 Comparison of Outflow before and Immediately after Pulsing

Sample 2
Fluid - glycerin
Head -1m
Confinement-
500 kPa
Porosity- 34%
Excitation
ω - 1 Hz
After-effect
30%

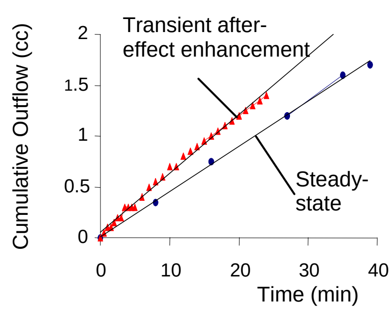

Figure 12 Comparison of Outflow before and Immediately after Pulsing

Sample 2
Fluid - glycerin
Head - 1m
Confinement-
0 kPa
Porosity 34 %
Excitation
ω - 1 Hz

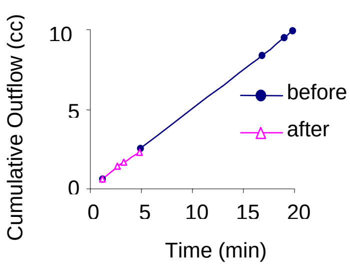

Figure 13 Comparison of Outflow Rates Before and after Pulsing

Sample 2
Fluid-glycerin
Head - 1m
Confinement-
500 kPa
Porosity- 34%
Excitation-
ω - 1 Hz

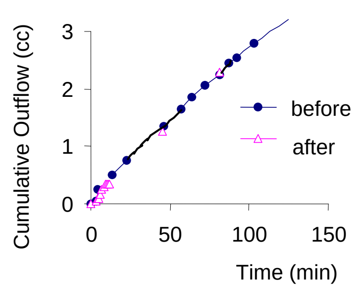

Figure 14 Comparison of Outflow Rates Before and after Pulsing

Sample 1
Fluid – paraffin oil
Head - 0.6m
Porosity - 34.2%

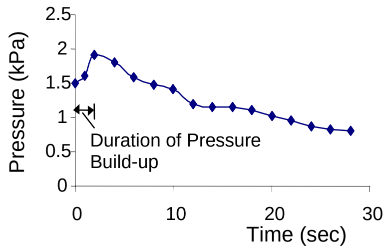

Figure 15 Pressure Reaction to One Pulse

Sample #2
Fluid - glycerin
Head - 1m
Confinement - 0 kPa
Porosity – 34%
Excitation ω - 1 Hz
Increase:
0.25 kPa/min

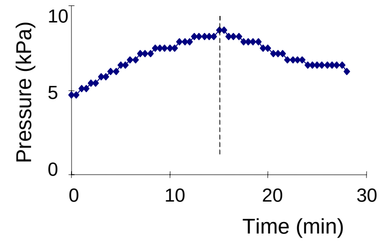

Figure16 Reaction of Pressure Transducer 1 During Test 2

Sample 2
Fluid - glycerin
Head - 1m
Confinement – 500 kPa
Porosity–34 %
Excitation ω - 1 Hz
Increase:
Transducer 1
0.17 kpa/min
Transducer 2
0.038 kpa/min

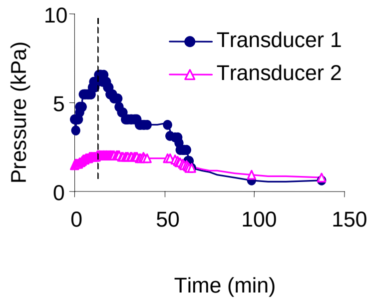

Figure 17 Pressure Reaction in Test 3

Sample #3
Fluid – glycerin
Head – 1 m
Confinement - 500 kPa
Porosity - 33.2%

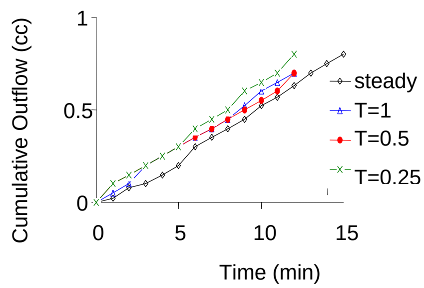

Figure 18 Frequency Test

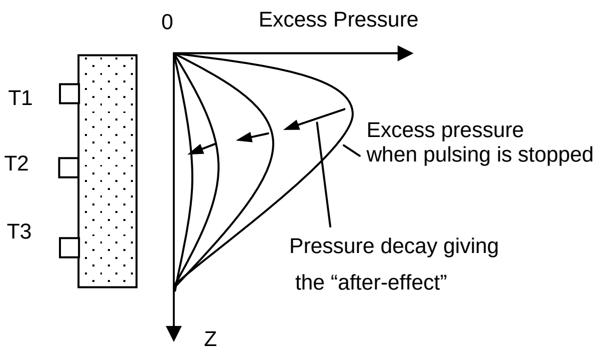

Figure 19 Pressure Decay Process