PRESSURE PULSE TECHNOLOGY:
AN ENHANCED FLUID FLOW AND DELIVERY MECHANISM

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ABSTRACT

Pressure Pulse Technology (PPT) is a proven injection technology that allows you to improve the flow of fluids in hydraulically connected porous media. It is based on a rigorous theory which demonstrates that not only is Darcy flow theory incomplete, but that many of the problems encountered in NAPL remediation can be overcome through the application of certain types of dynamic energy on a liquid phase. PPT has been extensively demonstrated in the laboratory as well as in field applications in the oil and environmental sectors. Pulsing is done so that the liquids repeatedly flow into and out of the wellbore and pore throats, generating intense mixing and superior dispersion, stabilizing displacement fronts, suppressing fingering, and greatly increasing contact area of a liquid with the porous media. PPT provides energy at the right scale: the pore scale. Effectively implemented PPT is the most efficient way to accelerate fluid flow, and disperse a liquid at the pore scale through a porous medium. Clearly, contacting the contaminant at the pore scale is critical to optimizing remedies, reducing rebound effects, and economizing remedial efforts for earlier exits from contaminated sites.

INTRODUCTION

Pressure Pulse Technology is the application of pressure variations at the megascale (Darcy scale) to cause dynamic flow processes at the pore scale. It enhances fluid injection and conformance of the injected phase. In the past, models of porous media have been based on the thermodynamics of molecular mixtures. This however does not account for dynamic variables, associated with pressure pulsing, such as porosity and saturation which describe the effect of mechanical work at the pore scale and how it effects the dynamics at the megascale.

Molecular diffusion, pore scale dispersion and megascale viscous fingering represent processes associated with the mixing of the fluids at the molecular scale, at the macroscale (pore scale) and the megascale respectively. Diffusion represents the mixing of the fluids at the molecular scale through the molecular diffusion of the phases. Dispersion occurs due to an adverse viscosity ratio, a variation in flow velocities within pores and due to pore and throat size distribution, all of which cause the fluids to mix at the pore scale and to remain distinct phases at the molecular scale. Viscous fingering is caused by an unstable mobility ratio between a displacing and displaced phase resulting in megascopic channels of the displacing phase passing through the displaced phase. The primary objectives of pressure pulsing are to enhance fluid injection, sweep efficiency and dispersion.

In the case of immiscible fluid flow the equations of motion for flow in porous media have been based on Muscat's equations. Here two equations identical in form to Darcy's equation are used to describe fluid flow and a concept called relative permeability is hypothesized which simply replaces permeability in Darcy's equation. However this system of equations may be seen to not be self-consistent and to be incomplete. What is missing from this description is that there are four independent permeability type terms; two in each equation, and more important there is a new dynamic variable requiring an additional equation to completely specify Newton's second law. The additional equation of motion allows for the dispersional motion of the fluid phases, which is enhanced by pressure pulsing. Of course a new dynamic variable has profound implications on the thermodynamics.

In the case of miscible flow in porous media the convection diffusion equation has been used in analogy with diffusive flow in the absence of a porous medium. The volume flux is used in place of the mass flux, the Dupuit-Forcheimer assumption. In this description dispersion was not being accounted for except through modifications of the dispersion tensor. In the proper description a Fokker-Plank equation is obtained and again the large scale mass fraction (megascopic concentration) brings additional saturation type information into the flow requiring an additional equation similar to the case of immiscible flow. Of course this again has severe implications on the thermodynamics and again allows for dispersional effects.

In the case of solid deformations, Biot theory has been used extensively. However this theory assumes that a single energy potential can be constructed for a porous medium thus eliminating porosity as a dynamic variable at the outset. As a result, this theory lacks a degree of freedom required to completely specify Newton's second law. Therefore the missing degree of freedom eliminates fluid flow associated with elastic deformations of the matrix, hence porosity waves. When porosity waves, which carry fluid through the medium, are allowed porosity becomes a dynamic variable.

The PPT theory has been shown to be more rigorous than previous theories, as it predicts certain effects that classical theory cannot. Among the predicted effects that arise from solutions to the series of equations is the existence of a porosity dilation wave that propagates at a velocity approximately $1/20^{th}$ of the compressional and shear waves (v_P, v_S). This wave has been measured and detected in wave trains; its velocity is a function of the viscosity and compressibility of the phases, as well as the stress and density in situ. In fact, the porosity dilation wave is in many ways analogous to a tsunami, which is a displacement wave (rather than a strain wave) in water that also travels at a small fraction of the P-wave (compressional wave) velocity. The porosity dilation wave has a velocity that is governed by the speed at which a displacement wave can travel in the liquid; in other words, its speed is that at which the pore liquid behaves incompressibly.

The micromechanical implications of a porosity dilation wave are very important. As the slow wave moves through the porous medium at a velocity of 80-200 m/s, elastic pore volume dilation and contraction takes place. This leads to large inertial effects at the pore throat scale because at these frequencies the pore liquids behave incompressibly. These inertial effects provide additional forces to the liquids; for example, accelerations applied to capillary interfaces between immiscible phases generate real forces: F = ma. These can help overcome the pressure barriers that arise because of the surface tension, helping the immobile phase to traverse through the pore throats and establish phase continuity.

APPLICATIONS OF PPT IN THE ENVIRONMENTAL SECTOR

There are numerous applications of PPT as it applies to the environmental sector including:

1. The enhancement of pump-and-treat systems one of the most notable methods of contaminant extraction.
2. Improved injection of *in situ* or “in-ground” remedies to treat the contaminant in place.
3. Rehabilitation of municipal, state, or federal water supply wells.
4. Aquifer recharge and storage programs.

In implications of PPT in the environmental sector represent:

1. An overall aid in the strategy for earlier exit strategies from contaminated sites hence reducing long-term financial obligations.
2. Turning marginal practices such as pump-and-treat systems into successful strategies.
3. The reduction in the number of injection points results in decreased drilling costs and less intrusion.
4. The ability to reach difficult locations such as under a building where no technology other than horizontal drilling can accomplish such tasks.

INJECTION PROCESSES AND TYPICAL PROBLEMS

Often, flow into the aquifer only takes place through preferential flow paths. When a treatment fluid is introduced, usually under quasi-static flow gradients, there is no possibility of bypassing these preferential flow paths therefore the treatment fluid may only affect a limited area. Therefore, a great majority of the formation is unaffected by the treatment fluid. In groundwater remediation using *in situ* remedies this characteristic is often the reason rebound occurs at a site: there is no pore scale mixing.

The treatment fluids, if not strictly water, are usually introduced by dissolution in an aqueous solution. The viscosity of this fluid will range from 1 centipoise (cp) for water to as high as +10,000 cp for an emulsion. However, these fluids are being injected into a medium containing a fluid with a viscosity 1 cp or greater. The high viscosity contrasts leads inevitably to instabilities, so that the injected specie contacts a very limited volume of the porous media.

In many formations, shallow or otherwise, it is also known from direct field measurements that the fracture gradient (lateral stress gradient) is on the order of 30-40% of the overburden, which can be less than a column of liquid to surface. This may give rise to another form of instability called hydraulic fracturing. As the fluid is pumped down the well, it may be under a fluid pressure larger that the lateral stress, thus it immediately creates fractures. These fractures are wide and of limited vertical extent because of the elevated compressibility of the material behind the wellbore. Only a few fractures are created, often only two vertical fractures extending from opposite sides of the wellbore, and fracture branching is seldom observed in laboratory tests or in the field for these conditions. As with fingering, diffusion into the reservoir from the fractures is slow, and only a small volume of fluids is affected.

PPT provides more uniform dispersion of an *in situ* remedy into the porous media, thus reducing the worst effects associated with channeling and fingering. A much larger volume of the porous media is affected, and the high degree of dispersion helps increase the efficacy of placed remedial fluids because the contact area with the porous media is greatly enhanced. PPT clears pore throats, aiding in the uniform placement of the *in situ* remedy. Instead of a fingered (or fractured) process, better conformance (placement) and pore scale mixing is achieved.

CASE HISTORIES

Queens, New York. The site (Figure 1) is the location of a former substation contaminated by dielectric fluid, an LNAPL. A five-day PPT waterflood pilot was undertaken to evaluate the efficacy of PPT in the mobilization of residual NAPL. Prior to the initiation of PPT, a static waterflood was performed to establish injectivity rates as well as water and free product levels in offset monitoring wells. This data was used as the base line for the comparative analysis of PPT.

The injection well was screened at 18 feet, one foot below the water table to ensure injection occurred at, or near the water table. The majority of monitoring and recovery wells were within 20 – 30 feet of the injection point. An initial test was done in January 2004 but was shortened due to abnormally cold weather that froze the water supply lines. However, even during the short tenure of the trial positive affects arising from PPT was evident from interface probe measurements in monitoring wells. The project was continued in March 2004 and initial results indicate that PPT had positive affects on the mobilization of the NAPL. Most evident was water level changes, changes in product thickness and measurability, and product reoccurrence following bailing.

Figure 1: Test site in Queens, New York.

Tonawanda, New York. Wavefront performed a pilot PPT program at a former coal tar gas plant in Tonawanda, NY. The site was an active pump-and-treat to recover a viscous NAPL. The zone of interest was located 20 feet below grade and consisted of two geologic units: a low permeability alluvial zone underlain by a higher permeability gravel zone.

For the first 25 days, a traditional static waterflood was applied by pumping surface water at 2.3 liters a minute (0.6 gpm) into a screened well that intersected both geologic units. The waterflood effects on pressures were measured in offset wells in each unit at 7.5 feet and 15 feet away from the injection point. The initial waterflood was followed by PPT injection at the same injection rate. Within hours, head increased in the alluvial unit and decreased in the gravel unit as compared to pressures seen during the static injection (Figure 2). In other words, the application of PPT resulted in more water flow through the lower permeability unit, showing the capability of PPT to limit the effect of permeability contrasts.

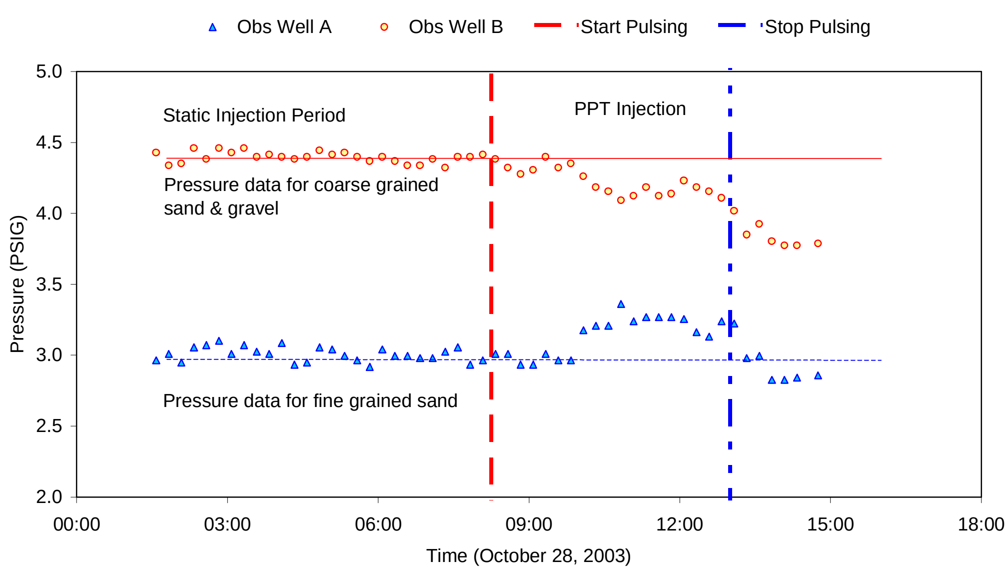

Figure 2: Pressure changes in the offset well 7.5 feet from the injection point

Unfortunately, the well soon failed and injection water starting coming to surface immediately along side the casing between the casing grout-soil contact. It appeared that the failure was due to the lack of competent grouting. Pressures during the PPT injection had stayed below recommended safety limits.

Austin, Texas. The Cape Fear Wood Preserving site in Fayetteville, North Carolina is a Superfund site with over 78,000 kg (172,000 pounds) of creosote contamination. Current efforts have focused on compiling a geosystem model from ground penetrating radar (GPR) surveys; laser induced fluorescence (LIF) surveys, drilling and DNAPL sampling. A bench treatability study was undertaken to evaluate the effectiveness of PPT to enhance surface dispersion and improve creosote recovery.

For the study a total of nine experiments were run on creosote contaminated porous media comparing static waterfloods, PPT waterfloods, and PPT surfactant floods. Both site soils and Ottawa sands were used in soil columns and a 2-d test cell. The 2-d test cell with interior dimensions of 25 x 36 x 1.9 cm is useful for determining 2-d fluid distribution. This effect is usually ignored by treatability studies, but a key factor when considering the usage of PPT.

The study indicated that PPT significantly enhanced the performance of both water flooding and surfactant flooding. The static waterfloods all recovered less than 50% of the creosote while the PPT waterfloods showed creosote recovery improvements of 10-15% over static flooding. When applied in conjunction with surfactant flooding the performance improvement was impressive. In the column and test cell experiments, PPT and surfactants removed 99.7% and 97% of the creosote, respectively. In the field soil experiments, a combination of surfactant flooding and PPT recovered 99.8% of the creosote with a starting saturation of 10.5% after 3.3 pore volumes of surfactant. When the creosote saturation was increased to 85%, 95.8% of the creosote was recovered after only five pore volumes of PPT injected surfactant (Figure 3).

Broomfield, Colorado. PPT was used in a comparative study for the injection of a bromide tracer in very low permeability silty clay in Broomfield, CO. The comparative study had equal volumes of the bromide tracer injected by (1) conventional pressure injection, and (2) PPT injection. Of importance during the comparison was the distribution of the tracer in the subsurface and the time taken for the tracer to reach independent real-time monitoring points. PPT outperformed conventional injection practices having the distribution of the bromide seen in monitoring wells both up gradient and down gradient from the injection point. As well, bromide was seen in a larger number of well points. Conventional injection distribution was limited to down gradient wells and a scattering of wells showed traces of bromide. Additionally, through PPT injection the bromide tracer was seen in the independent monitoring wells in half the time taken using conventional injection, which demonstrates the positive attributes of PPT accelerating fluid flow.

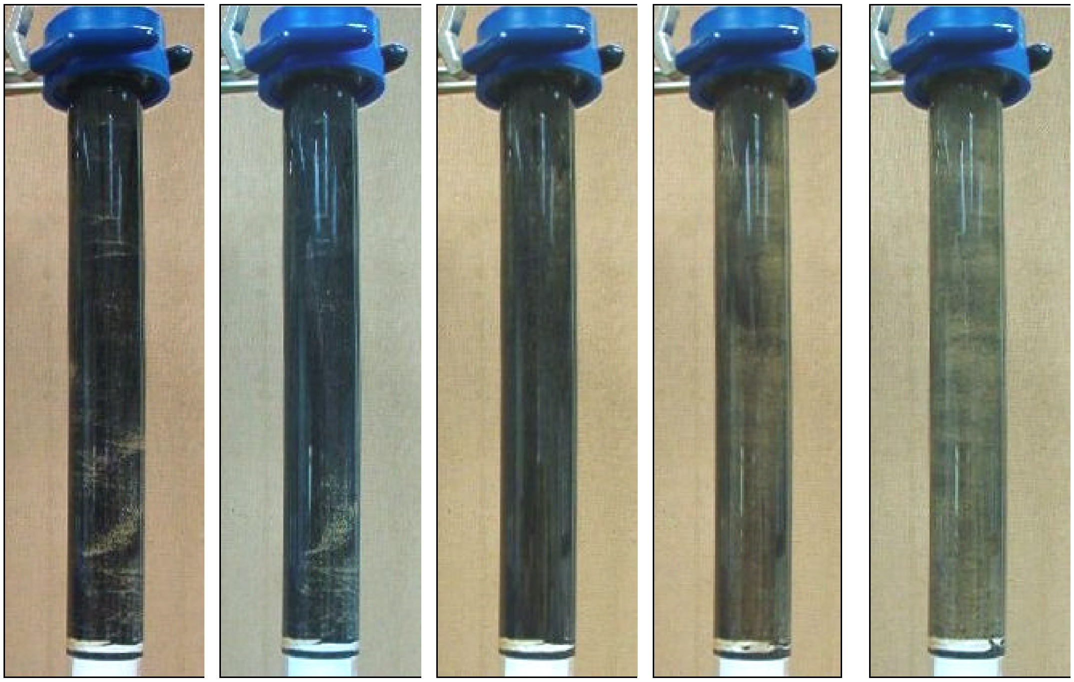

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Figure 3: PPT surfactant flood on an 85% creosote saturated site soil column. Total creosote recovery was 95.8% after five pore volumes.

Cape Canaveral, Florida. In January 2004, Wavefront conducted a single-well pilot project to evaluate the performance of PPT when injecting an emulsified zero-valent iron (EZVI). The project was run in Cape Canaveral where EZVI is being assessed as an *in-situ* treatment of a DNAPL composed primarily of trichloroethylene (TCE).

The well configuration was composed of one injection well flanked by two geoprobe offset wells, both at 3.5 feet from the injection well and approximately 130° from each other with respect to the injection well. The offset wells had Flute liners installed, which readily absorb oils and are designed to change colour when they come into contact with solvents.

During the PPT testing phase, the EZVI was injected in periodic stages with water until the injected volumes of EZVI and water totaled 65 gallons and 75 gallons, respectively. Figure 4 shows a sample pulse taken during the water injection with the pulse frequency decreased slightly for clarity. The actual pulse frequency was 40 pulses per minute. Following the injection, the Flute liners were pulled to evaluate the success of the test. Both Flute liners showed evidence of oil staining at 12-14 feet, with the darkest staining at approximately 13 feet. There was also some evidence of oil staining around 4 feet and 17 feet below surface.

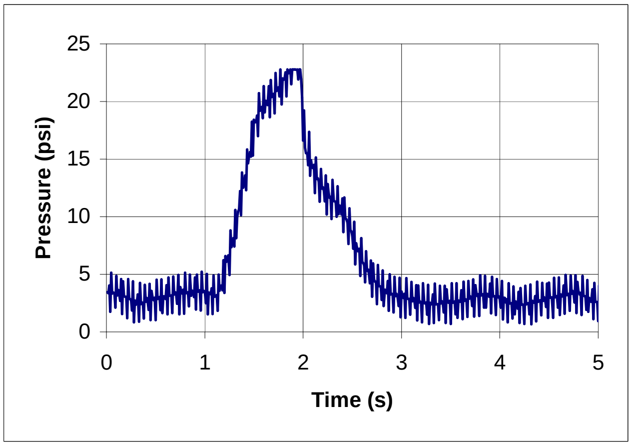

Figure 4: A sample pressure pulse. Note the sharp rise time and slightly slower decay time.

CLOSURE

Pressure Pulse Technology is a patented and authenticated technique for improved fluid flow. The performance claims of PPT have been verified by The Environmental Technology Verification (ETV) Program sponsored by Environment and Industry Canada.

The technology is based on established concepts: proper dynamic excitation generates waves where the liquid behaves incompressibility, and the porous medium undergoes dilation. Effectively implemented PPT is the most efficient way to accelerate fluid flow, improve injectivity, and disperse a liquid through a porous medium. It is the first technology to explicitly target pore scale mixing. Poor mixing at the pore scale has hindered the efficacy of *in situ* remedies: they do not treat the majority of the target pore volume. This ultimately leads to rebound events. PPT is demonstrated to mobilized trapped ganglia which give rise to dissolved phase constituents. Clearly, the ability to mobilize and remove the mass addresses many issues surrounding the dissolved phase.

Experience and further case histories will allow the benefits of PPT to be quantified more explicitly. However, indisputable field results generated since 1998 in both the oil and environmental sectors indicate they appear to be real and substantial. What does Pressure Pulse Technology mean to industry? In short, it means that industry may have to rethink many widely accepted concepts.