RATIONAL SOLITARY WELL SPACING IN SOIL REMEDIATION PROCESSES

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ABSTRACT

The present work addresses design aspects of soil remediation processes and suggests a rational well-spacing scheme to optimize the operational efficiency of systems and processes, considered in terms of pollute extracted per kW of mechanical power dissipated in pumps. The optimization scheme is proposed on the provisions of a universal map for steady-state two-phase flow in porous media, demarcating the process operational efficiency over the domain of the process operational parameters, i.e. the pollute/water flow-rate ratio and the capillary number. Process efficiency is considered over a formation volume containing a single well. Pertinent *DeProF*[2] model scaling law predictions for the reduced mechanical power dissipation are integrated across the formation control volume. Then, global values of energy utilization are estimated in terms of the process design parameters, i.e. the capillary number at the vicinity of the well-bore (Ca_0), the duty oil/water flow-rate ratio (r), and the radius of influence (ρ_c). Results indicate that, given the maximum permissible value of Ca_0, the overall efficiency of the process is increased with decreasing ρ_c.

KEYWORDS: two-phase flow in porous media, operational efficiency, rational well spacing, soil remediation, near well flow

1. INTRODUCTION

Pollutants, mainly in the form of complex chemical mixtures – such as total petroleum hydrocarbons (TPH), polychloro biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), heavy metals, and pesticides - enter the environment directly as a result of accidents, spills during transportation, leakage from waste disposal or storage sites, or from industrial facilities, and pose potential dangers to both the human health and the environment. Many remediation technologies have been developed to treat soil, leachate, wastewater, and groundwater contaminated by various pollutants, including *in-situ* and *ex-situ* methods. An extended review of biological, physical & chemical site-restoration technologies when soil and groundwater are contaminated by petroleum and related products, furnishing the respective processes, their applicability, advantages, limitations and concerns, the site-specific parameters as well as the related costs, can be found in [1].

According to the type of contaminated site, there are two major groups of applicable technologies: (A) *Soil remediation technologies*: these comprise soil washing, soil vapour extraction (SVE), land-farming, soil flushing, solidification/stabilization (waste fixation), biopiles, phytoremediation, bioslurry systems, bioventing, encapsulation, aeration, and (B) *Groundwater treatment technologies:* these comprise air sparging, groundwater pump-and-treat technology, passive/ reactive treatment walls, bioslurping, ultraviolet-oxidation treatment, biosparging, groundwater circulation wells, in-well air stripping, *in-situ* air and vapour stripping and vacuum vapour extraction, natural attenuation.

Many of these technologies implement injection/ extraction wells [1]. In *soil flushing*, contaminated soils are flushed *in-situ* by passing an extraction fluid through soil using an injection or infiltration process. Contaminated groundwater and extraction fluids are captured and pumped to the surface using standard groundwater extraction wells. In *groundwater pump-and-treat*, extraction wells are introduced at various locations in a contaminated aquifer, and the contaminants are removed with the pumped water. *Groundwater circulation wells* comprise a developing technology, used for removing contaminants from groundwater and saturated soils, implementing a process that continuously removes VOCs from the groundwater without bringing it to the surface. This circulation pattern is created in an aquifer by drawing water into- and pumping it through- a well, and then reintroducing it without reaching the surface.

The successful and cost-efficient treatment of a contaminated site depends on selection, design, and adjustment of the appropriate remediation technology, considering the properties of the contaminants, the soil and the

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[2] *DeProF* is the acronym for **De**composition in **Pro**totype **F**lows, see section 1.1

potential performance of the associated process which, in turn, depend on the proper system design as well as on the selection of conditions providing maximum operational efficiency (optimum operating conditions).

The core physical process in the aforementioned technologies is immiscible two-phase flow in porous media whereby one fluid ("water") is wetting the solid in presence of the other, non-wetting fluid (pollutant or "oil"). Possible flow modes are: *simultaneous, concurrent, forced flow of wetting and non-wetting fluids at preselected flow-rates*, *imbibition*, i.e., displacement of a non-wetting by a wetting fluid and *drainage*, i.e., displacement of a wetting by a non-wetting phase or air. These types of flow have two key characteristics: the disconnection of the non-wetting phase (pollutant /oil or air) into small fluidic entities -called *ganglia* and *droplets* (or *bubbles*)- and the formation of the respective wetting/non-wetting interfaces. Ganglia are fluidic entities (non-wetting blobs) that occupy the void volume of a few (1-10) pores. Droplets (or bubbles) are smaller fluidic entities, and any pore may contain many of these. It has been experimentally observed [2, 3] that during the simultaneous flow of two immiscible phases, the disconnected phase (non-wetting) contributes significantly (and in certain cases of practical interest, even exclusively) to the total flow. Furthermore, the flow-rate *vs* pressure gradient relation is found to be strongly non-linear, and to be strongly affected by the physical parameters that pertain to the fluid-fluid interfaces.

The scope of the present work is to furnish a rational methodology for designing more efficient soil/ groundwater remediation processes, specifically for those remediation schemes where injected /extracted fluids are administered through systems of rectilinear wells. The methodology implements the provisions of the *DeProF* theory for two-phase flow in porous media.

1.1 The *DeProF* theory for steady-state two-phase flow in porous media

The mechanistic model *DeProF* for immiscible steady-state two-phase flow in pore networks, developed by Valavanides & Payatakes [4], predicts the relative permeabilities of the two-phases using the concept of decomposition in prototype flows. Combining effective medium theory with appropriate expressions for pore-to-macro scale consistency for oil and water mass transport, the model takes into account the pore-scale mechanisms and the network-wide cooperative effects as well as the sources of non-linearity (caused by the motion of interfaces) and other complex effects.

Using the *DeProF* model, one can obtain the solution to the problem of steady-state two-phase flow in porous media in terms of the following set of independent variables, $\left(\mathrm{Ca}, r; \kappa, \theta_A^0, \theta_R^0, \mathbf{x}_{pm}\right)$ i.e., the capillary number, Ca, which is a measure of the ratio of viscous stresses over capillary pressure, defined as $\mathrm{Ca} = \tilde{\mu}_w \tilde{U}^w / \tilde{\gamma}_{ow}$ ($\tilde{\mu}_w$ is the viscosity of water, $\tilde{U}^w$ is the superficial velocity of water, and $\tilde{\gamma}_{ow}$ is the interfacial tension), the oil/water flow-rate ratio, $r = \tilde{q}_o / \tilde{q}_w$, the oil/water viscosity ratio, $\kappa = \tilde{\mu}_o / \tilde{\mu}_w$, the advancing and receding contact angles θ_A^0 and θ_R^0, and a parameter vector, $\mathbf{x}_{pm}$, composed of all the dimensionless geometrical and topological parameters of the porous medium affecting the flow (e.g. porosity, genus, coordination number, normalized chamber and throat size distributions, chamber-to-throat size correlation factors, etc), including the absolute permeability of the porous medium, $\tilde{k}$. (Note: a tilde ~ indicates a dimensional variable.)

Extended simulations of steady-state two-phase flow in a three-dimensional (3D) pore network of the chamber-and-throat type, using the *DeProF* model, showed that, in general, the reduced mechanical power dissipation may be analytically expressed as a scaling law,

$$W(\mathrm{Ca}, r) \equiv \frac{\tilde{W}\tilde{k}\tilde{\mu}_w}{\tilde{\gamma}_{ow}{}^2 \mathrm{Ca}^2} = \begin{cases} \dfrac{A(r)}{\left(10^6 \mathrm{Ca}\right)^{B(r)}} & r \le r_{\lim}(\mathrm{Ca}) \\ n/a & r > r_{\lim}(\mathrm{Ca}) \end{cases} \quad (1)$$

where, $\tilde{W}$ is the specific - per unit porous medium volume - mechanical power dissipation, and

$$A(r) = 10^{\sum_{i=0}^{3} A_i (\log r)^i}, \quad B(r) = B_0 + B_1 \log r \text{ and}$$
$$r_{\lim}(\mathrm{Ca}) = 10^{C(\kappa)\mathrm{Ca}^{D(k)}} \quad (2)$$

are functions of r, and A_0, A_1, A_2, A_3, B_0 and B_1 are appropriate scaling coefficients that take values according to the system parameters; $r_{\lim}(\mathrm{Ca})$ is the maximum value of the flow-rate ratio for which steady-state two-phase flow can be maintained. Typical values of the scaling coefficients as well as W(Ca, r) diagrams pertaining to Eqs. (1) and (2) are provided in [4].

1.2 Optimum operating conditions (OOC) for steady-state two-phase flow in porous media

The efficiency of the process, expressed as "the non-wetting phase transport per kW of mechanical power supplied to the system", may be assessed by the values of the energy utilization coefficient, f_{EU}, a macroscopic quantity defined by Valavanides & Payatakes [4] as follows:

$$f_{EU} = r/W \quad (3)$$

Simulations implementing the *DeProF* model suggest that conditions of optimum operation (read: maximum efficiency) exist for processes of steady-state two-phase flow in pore networks. The term '*optimum operating conditions*' (OOC) interprets those values of Ca and r (the operating parameters), for which the process efficiency takes one (or many) locally maximum values. As is depicted by the hump-shaped surface of Fig. 6 in [4], for every fixed value in Ca, there exists a unique value in r, r*(Ca), for which f_{EU} attains a locally maximum value. These provisions are described by a universal map for steady-state two-phase flow in porous media, demarcating the process operational efficiency [5].

Detecting and setting such conditions in a real process could eventually increase its efficiency. Now, when one-dimensional flow conditions are considered, the engineer may decide to operate the process at a certain value of the capillary number, Ca, dictated either by the power capacity of the available equipment or the maximum allowable stress of the underground formation (porous medium); then, he may tune the process to optimum operating conditions in terms of the flow-rate ratio, r*(Ca). Nevertheless, there are applications whereby isolated wells are used and one-dimensional flow conditions can only be attained far away from the well bore. The flow in the vicinity of the well bore is axisymmetric. Therefore, the Darcy velocity, hence the capillary number, change as $1/\rho$, to the radial distance, ρ, away from the well bore. In such cases, OOC can only be attained at a certain distance from the well bore. The engineer must then decide on the particular operating conditions for which the *overall* efficiency of the process is maximized.

2. PROBLEM DESCRIPTION AND ANALYSIS

Consider a horizontal, contaminated underground formation, say an aquifer. Consider the case whereby the formation is homogeneous and isotropic, and is confined between two horizontal impermeable planes. A typical soil flushing process is accomplished by passing an extraction fluid through the soil using an injection or infiltration process in order to mobilize the "oily" pollutants (say, TPH, PCBs, PAHs) that are trapped in the smaller pores of the formation, drive it to extraction wells, and then, to the surface. Injection and production wells may be arranged in various patterns depending on the morphology, extent and structure of the contaminated formation.

In the present work, we consider the simple case of one or many parallel isolated extraction wells (acting as rectilinear sinks), surrounded by injection wells distributed over the contaminated reservoir field. The wellbore radius of any extraction well is $\tilde{\rho}_0$.

Consider also a normal cylinder, of radius $\tilde{\rho}_c$, coaxial to the extraction well, such that the macroscopic flow velocities $\tilde{U}_i$, or flow-rate of each phase, $\tilde{q}_i$, i=o,w within this cylinder may be considered – within acceptable error – to be radial (Fig. 1). Mass balance for each phase imposes that

$$r(\rho) = r_0 \quad \text{and} \quad Ca(\rho) = Ca_0/\rho, \quad \rho > 1 \tag{4}$$

where, $\rho = \tilde{\rho}/\tilde{\rho}_0$ is the reduced radius ($\tilde{\rho}_0$ is the well radius),

$Ca_0 = Ca(1)$ is the Ca value at the well-bore walls, (5)

and r_0 is the oil-water flow-rate imposed by the process setup.

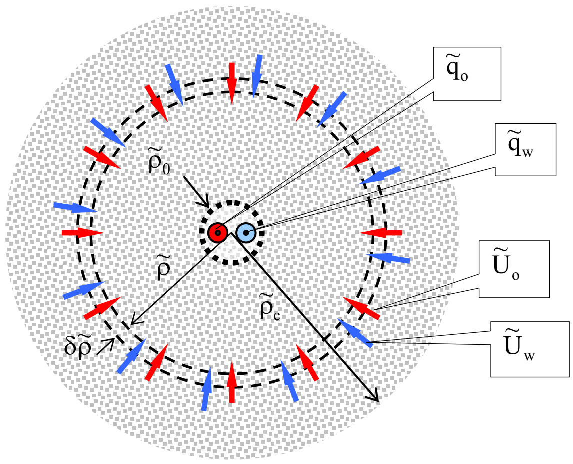

FIGURE 1 - The representative cylindrical volume where the analysis is carried out. The direction of macroscopic flow of oil, $\tilde{U}_o$, and water, $\tilde{U}_w$, is radial; oil and water are extracted with flow-rates $\tilde{q}_o$ and $\tilde{q}_w$ through the rectilinear well (perpendicular to figure) acting as a sink.

Given the physicochemical characteristics of the system (pollutant, water and porous medium characteristics), an expression for the process efficiency in terms of the radius of influence, $\tilde{\rho}_c$, can be derived. The efficiency of the process depends: (a) on the values of the design and operating parameters that can be tuned over a wide range and may be considered as "soft", and (b) on the values of the oil-water-p.m. system parameters, i.e. the physicochemical properties of the two phases and the p.m. characteristics, that can be tuned only over a narrow range and may be considered as "rigid". For example, the engineer has to decide on the extent of the recovery (formation) volume per well, dictated by ρ_c, a process set-up parameter. Similarly, the values of the imposed operating parameters, Ca_0 and r_0, can be adjusted so that the process is appropriately tuned. Note that the value of the admissible (or attainable) Ca_0 is limited by the strength of the formation material near the wellbore or the power capacity of the equipment (pumps etc).

The process operating cost is directly related to the reduced (over the unit p.m. volume) rate of irreversible transformation of mechanical energy into heat (the reduced mechanical power dissipation), $\tilde{W}_c(\tilde{\rho},\varphi,\tilde{z})$, needed to maintain two-phase flow over the recovery volume (the right circular cylinder, coaxial to the production well, extending from the wellbore radius, $\rho = 1$, to the influence radius ρ_c. The mechanical power dissipation is then given by

$$\tilde{W}_c(Ca_0, r_0; \rho_c) = \int_{\tilde{V}} \tilde{W} d\tilde{V} = 2\pi\tilde{\rho}_0^{\,2}\Delta\tilde{z}\frac{\tilde{\gamma}_{ow}^{\,2}}{k\tilde{\mu}_w} Ca_0^{\,2} \int_{\rho=1}^{\rho_c} W(\rho)\frac{1}{\rho}d\rho \tag{6}$$

The reduced, with respect to the reduced rate for one-phase flow (1ϕ) power losses, are estimated as

$$W_c(Ca_0, r_0; \rho_c) = \frac{\tilde{W}_c}{\tilde{W}_c^{1\phi}} = \frac{1}{\ln\rho_c}\int_{\rho=1}^{\rho_c} W(\rho)\frac{1}{\rho}d\rho \tag{7}$$

The idea is to set the values of the process design parameters, i.e. the values of Ca_0 and r_0 on the bore wall, and the radius, ρ_c, of the extraction volume (right cylinder), such that the process operates at its overall maximum efficiency.

A measure, f_c, of the efficiency of the particular process, may be defined by writing the ratio of the recovered oil flow-rate, $\tilde{q}_o$, over the total mechanical power dissipation, $\tilde{W}_c(\rho_c)$, within the recovery volume of radius ρ_c, and then, reduce it by the respective efficiency ratio for equivalent one-phase flow conditions (in terms of total flow-rate), to produce the global energy utilization coefficient for a recovery cylinder of radius ρ_c,

$$f_c(Ca_0, r_0; \rho_c) = \frac{\tilde{q}^o / \tilde{W}_c(\rho_c)}{\tilde{q}^w / \tilde{W}_c^{1\phi}(\rho_c)} = r_0 \ln\rho_c\left[\int_1^{\rho_c} W(\rho)\frac{1}{\rho}d\rho\right]^{-1} = \frac{r_0}{W_c(\rho_c)} \tag{8}$$

The benefit of using Eq. (8) is that all system characteristics (pertaining to water-pollutant-porous medium) are normalized-out, and the effects of the geometrical aspects of the process are revealed.

Incorporating the scaling law of the *DeProF* predictions for W from Eqs. (1) and (2), into Eq. (7) for the reduced specific mechanical power consumption over a recovery cylinder of radius ρ_c, yields

$$W_c(Ca_0, r_0; \rho_c) = \frac{1}{\ln\rho_c}\frac{A(r_0)}{B(r_0)}\frac{Ca_0^{\,-B(r_0)}}{10^{6B(r_0)}}\left[\rho_c^{\,B(r_0)} - 1\right] \tag{9}$$

and the energy utilization factor, Eq. (8), may now be expressed as

$$f_c(Ca_0, r_0; \rho_c) = r_0\frac{\ln\rho_c}{\rho_c^{\,B(r_0)} - 1}\frac{B(r_0)}{A(r_0)}\left(10^6 Ca_0\right)^{B(r_0)} \tag{10}$$

3. APPLICATION AND RESULTS

With the analytical expressions for $W_c(Ca_0, r_0; \rho_c)$ and $f_c(Ca_0, r_0; \rho_c)$ available through Eqs. (9) and (10), it is possible to investigate the effect of the operational, Ca_0, r_0 and design, ρ_c, parameters on the process efficiency. To this end, a typical system with oil/water viscosity ratio, $\kappa = 1{,}45$ (with scaling coefficient values given in [4]) was considered. Results are provided in Figure 2.

Examination of the diagram of Figure 2 reveals that:

(A) Under any fixed values of Ca_0 and ρ_c there corresponds a specific value of the oil/water flow-rate ratio, $r^*(Ca_0)$, for which the process attains maximum efficiency. This is more noticeable for low Ca_0 values and for recovery cylinders of relatively small diameter. Note that there are cases (for relatively high values of Ca_0 and ρ_c) where such a maximum is not attainable: the cylindrical surface outlined perpendicular at the far right end of the $f_c=10^{-9}$ plane represents the (Ca_0, log r_0) domain where two-phase flow is physically not sustainable.

(B) The global efficiency of the process, f_c, decreases significantly with increasing radius, ρ_c, of the influence cylinder. This is a direct consequence of the fact that as Ca drops sharply with increasing well distance, ρ, the effect of interfaces become pronounced (hindering the migration of non-wetting blobs -ganglia and droplets), and the respective local efficiency of the process is drastically reduced.

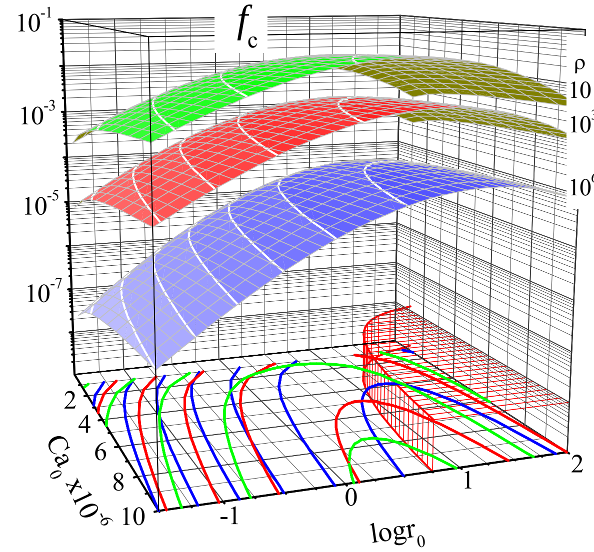

FIGURE 2 - Effect of the values of the operational parameters, i.e. capillary number at well, Ca_0, and flow-rate ratio, r_0, and for different radii, ρ_{c1}, ρ_{c2}, ρ_{c3}, of the recovery cylinder, on the global energy utilization coefficient, f_c, (flow-rate of extracted pollutant per kW of mechanical power consumed).

4. CONCLUSIONS

The problem of designing more efficient soil remediation processes implementing rectilinear sink (s) was considered under the provisions of the *DeProF* theory predictions.

The energy utilization coefficient, i.e. the flow-rate of recovered pollutant per unit mechanical power spent - originally determined for one-dimensional flow - was extended for radial flow conditions to account efficiency aspects of near-wellbore flow.

When a solitary sink is present, the energy efficiency of the process - for fixed values of the system parameters (physicochemical characteristics of the two fluids and porous medium) - depends not only on the values of the operational parameters Ca and r, but also on the size of the influence /remediation volume over which process efficiency is evaluated. The effective energy utilization coefficient, f_c, is drastically reduced with the influence radius, ρ_c, of the flushed p.m. volume. Therefore, when a distribution of wells is considered, f_c increases with the number of wells per unit area, or, well density. The presented analysis shows that the efficiency of the process is more sensitive in the adjustment of the flow-rate ratio, r_0, than in the adjustment of the reference capillary number near the well, Ca_0. The proposed design methodology has a greater added value when processes implementing relatively low values for Ca_0 ($<6\times10^{-6}$) are considered. When the formation material is weak and cannot sustain high pressure gradients across the well-bore, the engineer, having an upper limit for th Ca_0 value to cope with, may tune the flow-rate ratio, r_0, to a value that would optimize the overall operational efficiency of the process.

So long as only unit operational costs are examined, a “dense” well field should be sought for; nevertheless, the associated investment and managerial cost would increase with the number of wells (equipment, commissioning/decomissioning costs, management costs etc.). Therefore, in order to perform a global technoeconomic evaluation of any proposed field design, one should carry out a break-even analysis considering the fixed costs associated with the number of wells and the accompanying equipment against the operational efficiency of each well.

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REFERENCES

[1] Khan, F.I., Husain, T., Hejazi, R. (2004) “An overview and analysis of site remediation technologies” *Journal of Environmental Management* **71**, pp. 95–122.

[2] Avraam D.G., Payatakes A.C. (1995) “Flow Regimes and Relative Permeabilities during Steady-State Two-Phase Flow in Porous Media” *J. Fluid Mech.* **293**, pp. 207-236.

[3] Tallakstad, K.T., Knudsen, H.A., Ramstad, T., Løvoll, G., Maløy, K.J., Toussaint, R., Flekkøy, E.G. (2009) “Steady-State Two-Phase Flow in Porous Media: Statistics and Transport Properties” *Physical Review Letters* **102**, 074502 pp. 1-4.

[4] Valavanides, M.S. (2012) “Steady-State Two-Phase Flow in Porous Media: Review of Progress in the Development of the *DeProF* Theory Bridging Pore- to Statistical Thermodynamics- Scales”, *Oil & Gas Science and Technology*, **67**(5), pp.787-804 [http://dx.doi.org/10.2516/ogst/2012056]

[5] Valavanides, M.S. and Kamvyssas, G. (2013) “Operational Efficiency Map of Steady-State Two-Phase Flow in Porous Media Processes” *InterPore2013, 5th International Conference on Porous Media* Prague, 22-24 May [http://users.teiath.gr/marval/publ/Valavanides_Kamvyssas_InterPore2013.pdf]

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