

Two Phase Flow in Porous Media: Scaling of NAPL Displacement by Water Flooding on a X-Y Plane

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Abstract

When performing experimental work to study the recovery of NAPLs (non aqueous phase liquids) from porous media by water flood, scaling seems to be a critical step in the production of useful data that can be obtained from lab experiments. During many years, scaling was a very common technique in the petroleum industry. This technique was highly developed in the oil field in order to achieve greater efficiencies in the oil recovery process from porous media. However, this has not been widely investigated within the groundwater contamination and cleanup field. Many of the scaling parameters that were highly studied for petroleum recovery have not yet been studied for the recovery of NAPLs from contaminated aquifers. Through this investigation it is observed that a scaling equation based on a modification of the scaling equation presented by Craig et al. (1955) for petroleum recovery, can be used for scaling NAPL recovery from a contaminated aquifer. Laboratory experiments are performed which are based on the usage of a two-dimensional areal physical model that simulates an aquifer contaminated with a NAPL. Features of the physical model include background water flow and injection and recovery wells located in a five spot pattern.

1. Introduction

Spills of chlorinated solvents, like trichloroethylene (TCE) and other organics like gasoline, are common groundwater quality hazards in the industrialized world. Non-aqueous phase liquids or NAPLs are organic compounds, some of them chlorinated, which enter the saturated zone of an aquifer and fill up the soil pores with unwanted

organic matter that has low solubility in water and in many cases low viscosities. Over the years many researchers have investigated proper and efficient ways to remove these organic contaminants or NAPLs from the aquifers.

The recognition of soil and groundwater contamination by organic compounds has created new interest for the study of multiphase flow. The injection of water is a common practice to force non-aqueous phase liquids to recovery wells. The process of water injection into the aquifers to remove organics can be represented by a set of differential equations based on the unsteady state mass balance of the two phases (aqueous and organic) in porous media. In practice, however, it is difficult to reproduce laboratory experiments in the field because of a series of factors, which might include heterogeneities and capillary end effects. In order to account for this, scaling parameters have been developed, which allow investigators to scale from a laboratory experiment into field conditions and vice versa.

Scaled physical models have been used in the petroleum industry to study fluid flow in oil reservoirs for many years (Jawitz, 1995) and they have been used recently in the study of aquifer cleanups as well (Boyd, 1991). These models are used to represent actual field conditions in laboratory experiments, which are mainly executed in order to investigate or visualize the dynamics of fluid flow in a media; in this case a porous media. For example, a physical model was used by Nambi and Powers (2000) to investigate the dissolution of NAPLs in heterogeneous systems. Another 2-dimensional physical model was used by Walker et al. (1998) to investigate the removal of PCE in a saturated stratified media. Oil recovery techniques can be used for the recovery of contaminants in groundwater. However, the application of many scaling parameters previously developed for the oil industry have not yet been tested for their usage as scaling parameters for the decontamination of aquifers (Sundaram et al. 1994). Surundam (1994) investigated the removal of petroleum contaminants from soils. For his research he used a group of different scaling parameters to go from a 2-dimensional physical model to a larger field experiment. One of the limitations of laboratory experiments is that they represent idealized systems in which there are no local fractures, stratified permeability and the boundaries are controlled. Scaling equations try to overcome these limitations so that field conditions can be simulated in the laboratory.

Dimensionless parameters are used as scaling factors to scale a model to a prototype. These dimensionless groups can be obtained using a technique called dimensional analysis or another one called inspectional analysis. In the dimensional analysis, all the important variables that would govern a system are arranged so that the resultant is a dimensionless number. In the case of the inspectional analysis, the dimensionless groups are determined based on the governing equations and the boundary conditions for a system (Jawitz, 1995). An example of dimensional analysis would be the ratio $R=L/D$ where L is the displacing length and D is the depth of the aquifer. In this case, the dimensions of both parameters are in length, thus creating a dimensionless number. In the case of the inspectional analysis, one can refer to the principal flow equations that represent the system. From there try to obtain factors that would affect the system greatly, which could be viscosity, pressure, density, and others. By studying those parameters, a scaling number can be produced that includes the most important parameters, usually as a dimensionless number. For example N_c , which is the ratio of the viscous to the capillary forces.

The purpose of this paper is to describe the operation of a two-dimensional prototype model. The 2-D model was constructed to simulate NAPL displacement in a confined aquifer contaminated with non-aqueous phase liquids. Experiments were conducted to investigate the effects of scaling parameters on the recovery efficiency of NAPLs from a 2-dimensional physical model.

For this investigation field data and conditions used by Martel et al, 1998 were initially used as input data for the scaling equation. Curves for recovery efficiency versus injection flowrate were plotted to determine if the maximum recovery achievable would take place at the scaled injection flow rate.

2. Scaling

Craig et al. (1955) developed the following scaling equation for the one-dimensional displacement of oil from porous media by water-flooding:

$$\left[\frac{q_i \mu_o X}{\gamma \cos \theta} \right]_{\text{model}} = \left[\frac{q_i \mu_o X}{\gamma \cos \theta} \right]_{\text{field}} \quad (1)$$

Where

q_i = injection rate per foot of aquifer depth, μ_o = NAPL viscosity, χ = distance between wells, γ = interfacial tension (non aqueous phase and water), θ = contact angle of NAPL and water interface with rock surface. This last equation represents a non-dimensionless number which relates viscous forces and displacement distance to capillary forces. The development of this relationship is similar to the estimated maximum horizontal length of stable ganglion X_{max} where NAPL is near residual saturation (Mercer et. al, 1990)

$$X_{\text{max}} = \frac{2\gamma \cos \theta k}{\mu q a} \quad (2a)$$

where k is the permeability and q is Darcy's velocity. Equation 1 would be true for soils with similar media, thus similar permeabilities.

Equation 2a was derived from equation 2b which describes Darcy's law for the individual fluids

$$q_{wi} = -\frac{k_{ij} k_{nw}}{\mu_w} \left(\frac{\partial P_w}{\partial x_j} - \rho_w g \right) \quad (2b)$$

Where k_{ij} is the intrinsic permeability and k_{nw} is the relative permeability of the NAPL and water. The relative permeability is not used in equation 2a given that at this point an approximation can be made were the relative permeability is ~ 1 . The gravitational term is canceled on a horizontal plane. Performing unit analysis, it was determined that the

number 2 is in units of $1/s \text{ m}^3$. A similar equation was presented by Dekker and Abriola (2000), where they developed a scaling number N_c , which was very similar to the equation presented above. This is presented in equation (2c)

$$N_c = \frac{k\Delta P}{L\gamma_{ow} \cos \theta} \quad (2c)$$

For our laboratory experiments, since we had no actual way to measure the contact angle between the two phases and the solid surface, we solved for $\cos \theta$. When scaled, the cosine of the angle should be a dimensionless number and it is assumed that it will remain constant for soils with similar chemical properties and similar aqueous and non-aqueous fluids. Thus by rearranging equation (2a)

$$\frac{X_{\max} \mu q a}{2\gamma k} = \cos \theta \quad (2d)$$

and should remain constant for all scaled cases.

If the cosine of the contact angle is about the same in the laboratory and in the field under similar conditions, equation (1) can be then modified to produce equation (3)

$$\left[\frac{q_i \mu_o X d_{50}}{2\gamma k} \right]_{\text{mod el}} = \left[\frac{q_i \mu_o X d_{50}}{2\gamma k} \right]_{\text{field}} \quad (3)$$

This scaling equation was developed from the differential equation of the flow process.

The physical model used by Craig et al (1955) to develop equation 1 simulated a horizontal flooding for oil recovery in porous media but it did not include a natural groundwater or background flow. Assuming the groundwater flow in the field is very small compared to the injection flow, then the fact that the groundwater flow is not present in the laboratory experiments should not matter. For example, in the case of the field test presented by Martel et al (1998) the background flow velocity was just about 1/6 of the injection flowrate velocity. In other words, the groundwater flow should not change significantly the displacement conditions for injection flows much greater than the groundwater flow. As observed in the lab, a zone is created where the pressure produced by the injection flow is the same as the pressure produced by the head of the aquifer. When the forces (pressures) are the same but in opposite directions there will be no fluid displacement. This will create an area within the model were very small or no fluid displacement will occur.

For this research pump and treat operations will be simulated in the laboratory at different injection rates using a 2-dimensional physical model. One injection rate Q_s (or Q scaled) is obtained from the scaling equation (3). A range of $Q_s \pm 1$ ml/min is used and recoveries related to them are plotted as a function of water injection rate. Results are expected to represent the effect of injection flow rate on NAPL recovery.

3. Experimental materials and methods

3.1 Prototype model design

A two dimensional prototype model was designed to meet the objectives of this investigation. Given data provided by Martel et al.(1998), it was determined that a cell with inside dimensions 30 cm length x 15 cm width should be used for the investigation because it would be easy to handle but at the same time would produce reliable data. It was determined that for this investigation a single layer of glass beads with 3mm diameter would be used to produce a 2 dimensional layer. So, the inner thickness of the model was 0.3 cm. Given these dimension, it was determined by equation 3 that if scaled for hexane recovery from the cell with interfacial liquid tension 51 dyn/cm and absolute viscosity 0.33cP (Mercer and Cohen, 1990), an injection flow rate of 3.4 ml/min should be used in as our scaled injection rate Q_s .

In order to construct the cell, two lexane sheets were used as see-through plates. An aluminum frame was located on top of one of the Lexane sheets. This metallic frame contained a rectangle in the middle of dimensions 15cm x 30 cm. Two aluminum screens with 1 mm diameter holes were located at the extremes perpendicular to the flow. The two screens were connecting the inner chamber with two outer chambers which purpose was to distribute the background flow evenly. The thickness of the aluminum frame was 3mm. Later, another Lexane sheet was placed above the frame and then closed tight using screws. Teflon tape was put within the Lexane and the aluminum to avoid any leaks. On top of the upper Lexane sheet, connectors (1.6 mm diameter) were placed one above each of the chambers, one in the middle of the rectangle and four others surrounding the middle one in a five well pattern, with a distance of 7.5 cm from well to well. Figure 1 shows the top and side view of the prototype model. This model was developed to handle injection flow rates ranging from 1-4 ml/min. This way it could handle a wide variety of organic contaminants with a given ratio of viscosity and interfacial tension.

3.2 Experimental procedure

A water injection flow rate, Q_s was calculated for the laboratory model base on field data reported by Martel et al, 1998, and the scaling equation (3). It was determined that the scaled injection rate for our physical model and hexane should be $Q_s=3.4$ mL/min. Hexane was selected as the appropriate organic to use fro this investigation, because the scaled flowrate could be produced with the available pumps and it would be safe for the Lexane body of the model. A schematic of the experiment is presented in figure 2. The non-aqueous phase liquid, in this case hexane, was colored using SUDAM III. The bed was packed with one layer of 3mm glass beads. The cell was filled with distilled, de-aerated water. During the water saturation process the cell was placed in a vertical position and water was injected from the bottom to be able to displace the air on top. When the cell was fully saturated with water hexane was released into the cell from the NAPL reservoir. When the organic started filling the cell, it displaced most of the water

that was in the cell. The displaced water was collected from the bottom well and the volume of water displaced from the cell was measured in order to calculate initial water saturation (S_i).

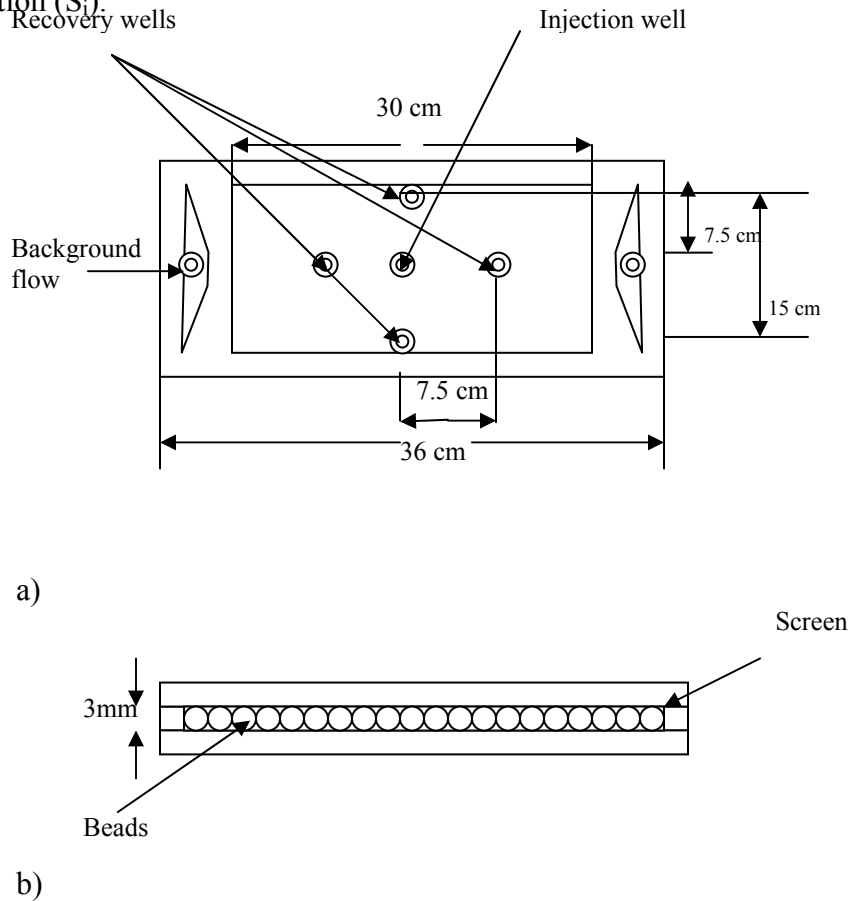


Figure 1, a) Top view prototype model, b) side view prototype model

When the contamination was finished (no more water was being displaced) the cell was placed horizontally and all of the valves connecting the pumps with the wells were opened, including background flow. Next, the stopwatch was started and all of the pumps were activated, beginning with the pump that was used for water injection. The experiments were performed with the cell in the horizontal position. As shown in Figure 1, the well located in the middle of the cell was used as an injection well where water was injected at a constant (average) flow rate q , and the surrounding four wells were used as recovery wells (in a five spot pattern) and approximately $q/4$ was pumped out of each well. The product was recovered in volumetric vials and the hexane volume, the water volume, the number of the well they came from, and the time at which they were

removed were reported for each sample. Also, some fluid that was displaced to the exit chamber was removed and measured as a function of time.

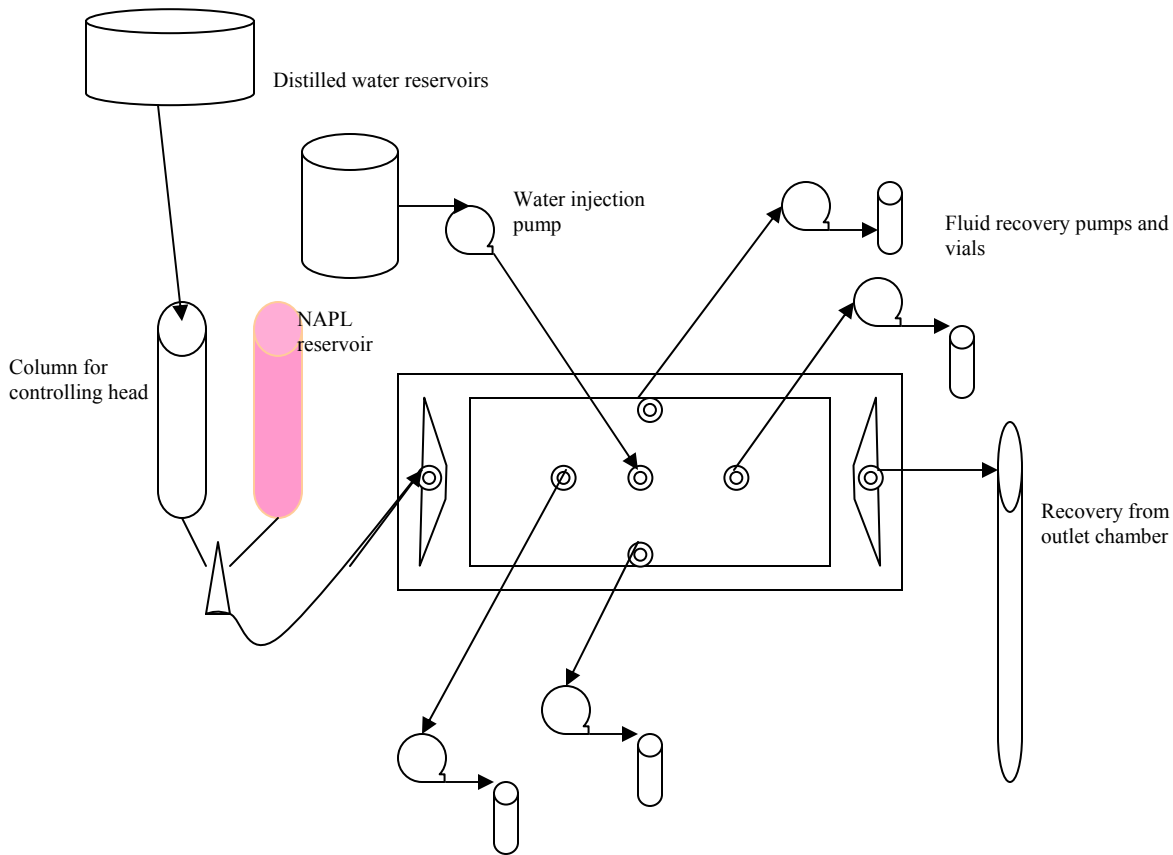


Figure 2. Schematic of experimental apparatus

Control Head

The background head was kept constant by using one open column connected to the inlet connector at the inlet chamber as shown in Figure 2. The column was filled from another container and excess water would fall into a plastic tray that was located underneath it. At the outlet, the tubing was kept at a specific height with an open end.

NAPL, Water and Dye

Distilled water was used for the experiment. A mild stream of nitrogen was allowed to bubble through the distilled water for approximately 2 minutes immediately before initiating each experiment to remove dissolved air contained in the water. Hexane was dyed by adding 50mg/L of SUDAM III. The NAPL was kept in a closed glass container until ready to inject into the cell to avoid volatilization.

Recovery data for analysis

The hexane volumes recovered in each well were measured, as well as the total liquid recovered in a given time. From there, the saturation in the cell was calculated as a function of water injected, as well as the percentage hexane recovered.

4. Experimental Results

Eight experiments were run using the two-dimensional model packed with 3 mm diameter glass beads at different injection flow rates. Hexane was used as the representative NAPL for all experiments. The injection flow rate derived from the scaling equation was $Q_s=3.4$ mL/min. Dividing the injection flowrate by 6 gave the background water flow of approximately 0.5 mL/min. This was done in order to use similar conditions as Martel et al. (1998). Injection flow rates used for different experiments ranged between 2.6 and 4.6 mL/min on average. However, variation in flow velocity was observed throughout each experiment (± 0.1 mL/min) which can be attributed to changes in NAPL saturation and fluid relative permeabilities during the flooding process. The average injection flow rate was calculated by adding all liquid (water and hexane) removed from the cell and dividing it by the total recovery time. Figure 3 shows the percentage hexane recovery as a function of water pore volumes injected for the different injection flow rates. As shown in Figure 3, the maximum recovery differed in each case, depending on the water injection flow rate used. At flow rates close to the scaled flow rate of 3.4mL/min (using equation (3)), it can be seen how the hexane recovery is greater. Also it can be seen in the figure, how at very low or very high injection flow rates, the recovery is reduced significantly. The reason for that can be that at very low flow rates, the displacing fluid does not have enough force to push the displaced fluid given the low injection speed. On the other hand, at very high injection flow rates, the velocity of the displacing fluid is so high, that it does not go around the soil particles to displace the hexane. Instead, it goes right through, maybe creating some kind of fingering or channeling, thus allowing large quantities of NAPL to stay untouched in the porous media. Non-uniform recovery can be observed in figure 4.

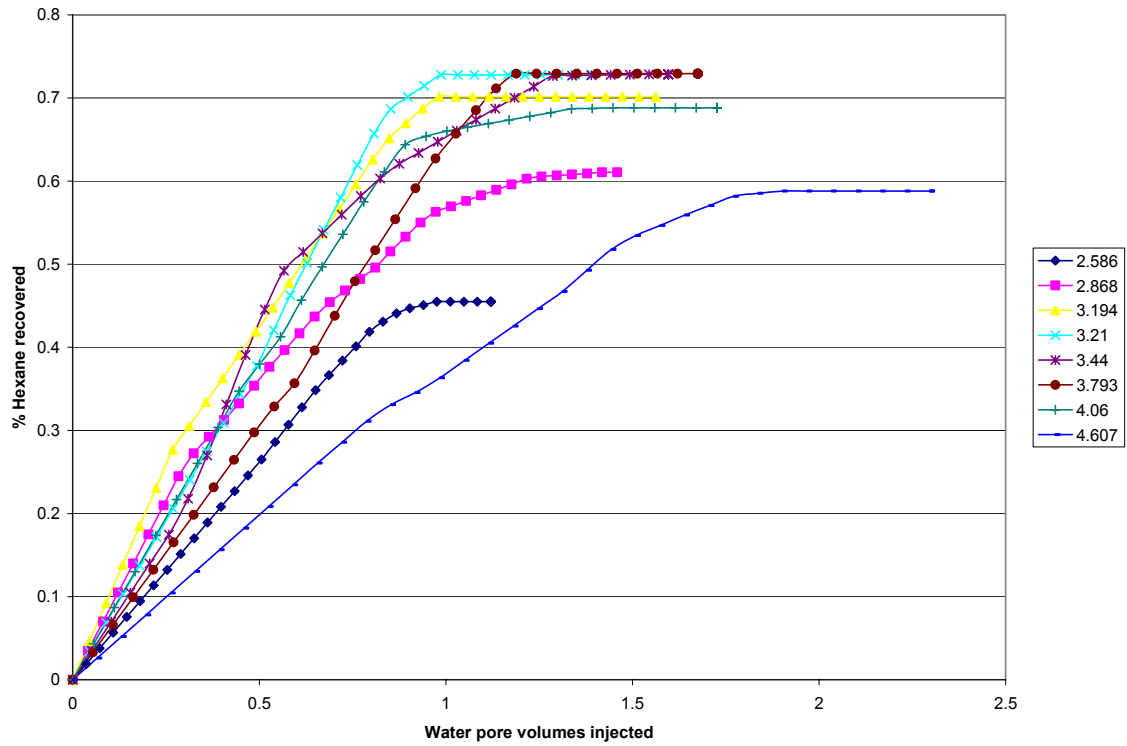


Figure 3. % Hexane recovered at different injection flow rates

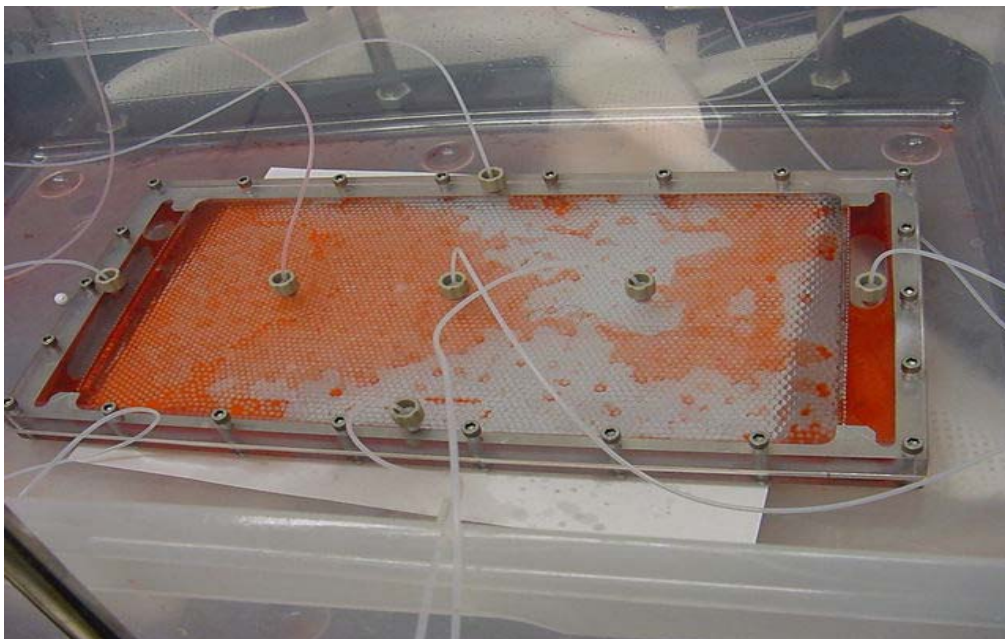


Figure 4. Non-uniform recovery in the porous media

The effects of injection flow rate on hexane recovery are illustrated in Figure 5. As it can be seen in the figure, different recoveries are achieved at different injection flow rates. However, the maximum recovery is not achieved at the largest or smallest injection flow rate, but instead it is achieved at a flow rate located in the middle range, very close to the injection flowrate obtained from the scaling equation.

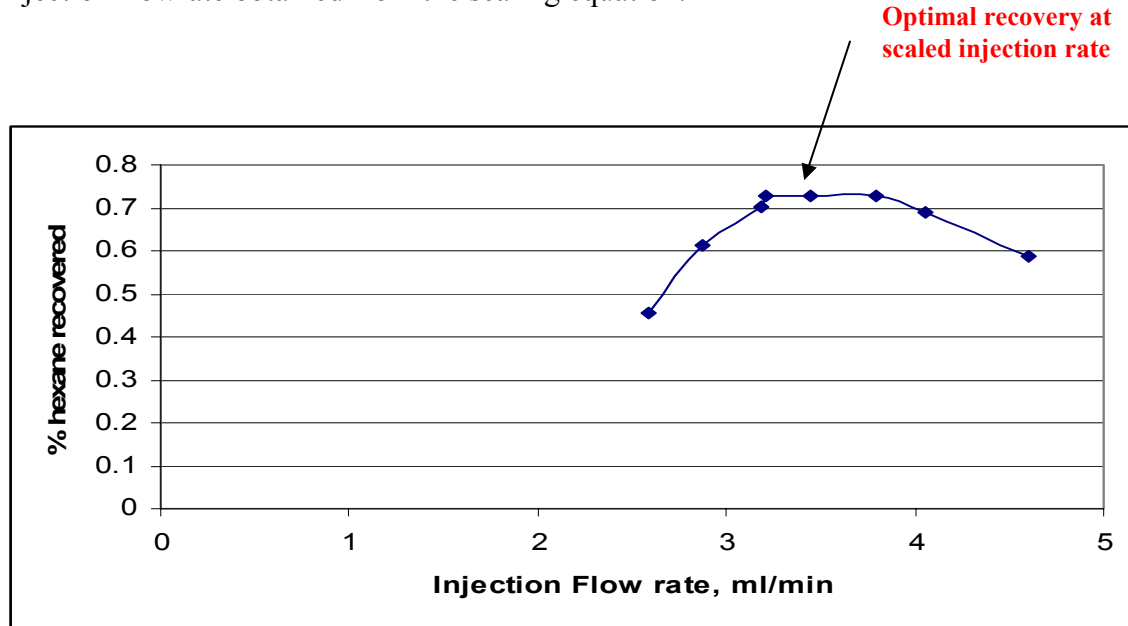


Figure 5. Hexane recovered vs. injection flow rate.

As shown in Figure 5, greater recovery efficiencies were achieved at injection flow rates close to the scaled water injection flow rate. Also it can be seen in the figure, how at very low or very high injection flow rates, the recovery is reduced greatly.

Table 1 was developed, which relates equation 3 and the recovery efficiency.

Injection rate, mL/min	$\left[\frac{q_i \mu_o X d_{50}}{2 \gamma k} \right]$	Hexane recovery efficiency, %
2.586	2.91×10^{-11}	0.455
2.868	3.22×10^{-11}	0.615
3.19	3.58×10^{-11}	0.702
3.21	3.61×10^{-11}	0.728
3.44	3.86×10^{-11}	0.728
3.793	4.26×10^{-11}	0.729
4.06	4.56×10^{-11}	0.688
4.607	5.17×10^{-11}	0.588

Table 1. Hexane recovery efficiencies scaling parameter based on equation(3).

Table 1 shows that if numbers obtained using equation (3) are within 3.5×10^{-11} and 4.5×10^{-11} , greater recovery efficiency can be reached for our 2-D physical model and hexane.

It was observed that at flow rates about 1/6 of the injection flow rate, the background flow is so small, that it is not capable of displacing any of the NAPL. The contaminated zone enclosed in the cell is not influenced by the background water flow. For this reason, modified scaling parameters initially developed by the oil industry that did not take into account the background water flow can be used in the case where groundwater flow is present, since this will not influence the results. The fact that the background flow is not influencing the flow within the boundaries allows researchers to use the model in the direction of the flow and in any perpendicular direction that might not be the direction of the flow.

As it can be seen in equation (3), the distance x (linear distance between injection and recovery well) is one of the variables used. This can be addressed in two dimensions by the fact that in a five spot pattern, the distance x is the same distant from all recovery wells to the injection well.

5. Summary and conclusions

A 2-D laboratory experiment was performed to investigate if a modified scaling equation from the one presented previously by Craig et al. (1955) for oil recovery by water flooding in porous media can be used to scale for aquifer cleanup by water flooding when contaminated by non-aqueous phase liquids. A two dimensional physical model was designed, constructed and operated to investigate hexane recovery by water flooding using a five spot pattern. Areal contaminant recovery from an aqueous porous media was observed to reach a maximum for a specific range of injection rates. Data from field test developed by Martel et al (1998) were used as input parameters in a scaling equation to obtain a scaled injection rate for which NAPL recovery should be produced given specific characteristics of the prototype model. It was observed in the laboratory that contaminant recovery is lower at flowrates higher and lower than the scaled rates, which can be caused by the microscopic forces acting on the contaminant globules at different flow rates. The reason for that can be that at very low flow rates, the displacing fluid does not have enough force to push the displaced fluid given the low injection speed. On the other hand, at very high injection flow rates, the velocity of the displacing fluid is so high, that it does not go around the soil particles to displace the hexane. Instead, it goes right through, maybe creating some kind of fingering or channeling, thus allowing large quantities of NAPL to stay untouched in the porous media.

It was observed that with water injection as the only recovery process, a maximum recovery for hexane of about 70 percent can be reached in a five spot pattern with 3 mm glass beads as the porous media at an injection rate close to 3.44 ml/min. This means that residual NAPL is about 30 percent Recoveries at different injection flowrates indicate

that better recoveries can be achieved at injection flowrates close to the scaled injection rate. One of the reasons this scaling equation is likely to work under these conditions is the fact that the background flowrate is very small compared to the injection flowrate and thus does not affect the flow patterns within the cell.

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