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# SIMULATION OF DENSE NON-AQUEOUS PHASE LIQUID REMEDIATION THROUGH STEAM-ENHANCED EXTRACTION

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## ABSTRACT

Steam-enhanced extraction has been reviewed by many researchers as an innovative technology to remediate dense non-aqueous phase liquid (DNAPL) from subsurface. However, the application of steam-enhanced extraction to heterogeneous subsurface conditions is still obscurity and its implementation is limited due to steam flow sensitivity to site characterization. Two-dimensional (2-D) simulations were performed to assess the efficiency of steam-enhanced extraction in remediation of heterogeneous subsurface contaminated with tetrachloroethylene (PCE) spill. The simulation was performed with four different steam injection rates. The results shows that increased in steam injection rate will increase the PCE remediation time. The steam injection with the rate of $1.0 \times 10^{-4}$ kg/s was successfully removing 100% of the PCE. There are significant impacts in the difference in remediation time with the increment approximately 20 min, 40 min and 70 min for every $2.0 \times 10^{-5}$ kg/s increment. The dominant mechanisms of PCE removal is physical displacement through vaporization and co-boiling enhanced by steam distillation and steam stripping. The simulation results of steam-enhanced extraction for PCE removal was compared with surfactant-enhanced method implemented in existing experimental study. It was discovered that the time required to remove PCE using steam-enhanced extraction is four times faster than the time required to remove PCE using surfactant-enhanced method. This shows the capability of steam-enhanced extraction to recover contaminant more effectively. Steam-enhanced extraction has a greatest potential to decrease clean-up time which will offset greater capitol cost of the system.

**Keywords:** dense non-aqueous phase liquid, tetrachloroethylene, steam-enhanced extraction, subsurface remediation.

## INTRODUCTION

Dense non-aqueous phase liquid (DNAPL) is a group of liquid that classified as soil and groundwater contaminants when hydrocarbon liquid spills or leaks into the ground. The DNAPL is denser than water and cannot mix with water. The DNAPL tends to sink below groundwater table and will stop when reached impermeable layer. The penetration of DNAPL into an aquifer makes them difficult to locate and remediate. The DNAPL is a poisonous and dangerous substance. It can cause burning in the mouth, throats and stomach pains. Direct contact with DNAPL can cause severe skin irritation, surface eyes feels burning, convulsions and mental confusion, kidney or liver problems, unconsciousness, and even death.

Steam-enhanced extraction has been studied as an innovative technology for subsurface remediation adapted from oil recovery enhancement method by petroleum industry (Balshaw-Biddle *et al.*, 2000; Heron *et al.*, 2005; Hunt *et al.*, 1988). Extensive laboratories, simulations and field research of steam-enhanced extraction have proven to be efficient subsurface remediation methods. However, the application of steam-enhanced extraction to heterogeneous subsurface conditions is still obscurity. The implementation of steam-enhanced extraction is limited depending on site characterization which affects the sensitivity of steam flow. Some effort has to be made to establish this technology in remediation practice.

The use of steam-enhanced extraction is importance to identify and visualize its effectiveness and capability of DNAPL removal in saturated porous media. These results can be used to evaluate possible conservancy effects for an adequate dissolution of DNAPL. This will provide characterization and remediation to avoid the spreading of contamination. The aim of this study is to investigate the process of migration and removal of DNAPL in heterogeneous saturated porous through model simulation. The objectives are to simulate the migration and removal of DNAPL from saturated heterogeneous porous media in 2-D model, to identify the dominant mechanisms of DNAPL removal during steam-enhanced extraction and to evaluate the performance and efficiency of steam-enhanced extraction during DNAPL removal.

## METHODOLOGY

### Steam-enhanced extraction

Steam-enhanced extraction (SEE) was adapted from enhanced recovery oil method used by petroleum industry. In petroleum industry, the method was discontinued because of uneconomical process cause by ineffective extraction of original oil from reservoir. Since 1960s, an extensive laboratory and field research has been done to examine the used of steam-enhanced extraction for remediation of DNAPL. Application of steam steam-enhanced extraction for DNAPL remediation is suitable

compared to petroleum industry cause by different subsurface conditions such as shallow/deep and unconfined/confined subsurface (Davis, 1998).

Steam-enhanced extraction is in-situ thermal treatment method for DNAPL remediation using steam injection and extraction through well. SEE process initiated by injection of steam into subsurface. The steam gives its latent heat of vaporization to the soil and groundwater. Condensation occur when steam change to hot liquid water from its gaseous form due to loss of heat to soil and groundwater. Continuous injection of steam causes the soil and groundwater near injection well to reach steam temperature.

This process continuously affects the ambient soil and groundwater creating a moving front variable temperature of water and steam. When the movement of variable temperature of water and steam reach contaminated DNAPL area, it reduces the DNAPL viscosity (Davis and Lien, 1993; Edmondson, 1965; Poston et al., 1970). The residual and adsorbed DNAPL in soil may vaporize into gaseous phase thus causes the DNAPL to move towards front together. The DNAPL gaseous phase may turns into DNAPL aqueous phase, DNAPL phase and DNAPL adsorbed phase due to ambient temperature of soil and groundwater. This process will continuously occur until it reaches the extraction well (EPA, 2006).

The removal mechanism which enhanced DNAPL remediation during steam-enhanced extraction is physical displacement, temperatures, steam distillation and displacement, depressurizing process and enhancement of DNAPL desorption from soil. The physical displacement was occur when the immiscible liquid of DNAPL greater than DNAPL residual saturation and when DNAPL in gaseous phase due to steam. The physical displacement also occurs due to groundwater flow pushing the DNAPL moving front and hot water formed by steam condensation which reduces the DNAPL viscosity and makes it move together (Herbeck et al., 1976).

The increased in temperature will reduce the capillary and interfacial forces between DNAPL and soil. Thus, reduce the DNAPL residual saturation and increase DNAPL mobilization. This will increase DNAPL saturation and may result in formation of liquid DNAPL which can displace by physical forces. Steam distillation affected by liquid composition, temperature and pressure occur when injected steam sweep the DNAPL vapor in front of condensation vapor. This process increases the DNAPL saturation and addition of DNAPL vapor. Formation of liquid DNAPL occur when the DNAPL saturation exceed its solubility at ambient temperature.

The enhancement of DNAPL remediation during steam-enhanced extraction by cycling of steam injection and vacuum extraction after breakthrough of steam at extraction well is called depressurizing process (Newmark and Aines, 1995; Udell and Stewart, 1989). The depressurizing process initiated by vacuum extraction process alone after steam breakthrough at extraction well

with no steam injection. This will cause the thermodynamic system unstable. To stabilize the thermodynamic system, temperature shall be reduce with reduce pressure.

Heat was loss by DNAPL and water evaporation extracted by vacuum extraction. After thermodynamic system is stable, the steam was injected at low pressure cause the heat to recharge to drive the DNAPL evaporization. This would increase the removal rate and reduce overall clean-up time (Itamura and Udell, 1995). The amount of heat required depends in DNAPL types and soil types. The desorption rate shows that whether there was a strong bond formed between soil and DNAPL (Lighty et al., 1990).

## T2VOC TOUGH2 simulation program

T2VOC is a program designed to simulate numerical models of contaminant transport specific to be an organic chemical's transport in one, two and three dimensional nonisothermal multiphase system. T2VOC was developed to simulate contaminant migration, extraction and removal of contaminants from soil and groundwater including the migration of non-aqueous phase liquids (NAPL) either light or dense in variably saturated media. The program has been developed at Lawrence Berkeley National Laboratory from early 1980s by Karsten Pruess, Senior Scientist in the Earth Sciences Division of the Lawrence Berkeley National Laboratory in Berkeley, California (Falta et al., 1995).

The multiphase system in T2VOC TOUGH2 simulation program assumed to include mass component of air, water and volatile water soluble organic chemical. However, air containing nitrogen, oxygen, etc. is assumed to be a single"pseudo component" with averaged properties. The program is applicable to strongly water-soluble organic compounds. Flow of gas, aqueous and NAPL phases follows multiphase extension of Darcy's law including pressure, gravitational force, relative permeability and capillary pressure (Falta et al., 1995).

Assumptions have been made that no chemical reactions occur except interphase mass transfer, adsorption of chemical to solid phase and biodegradation decay. Vapor pressure lowering effects due to capillary forces is not included. Heat transfer effects are fully accounted and overall thermal conductivity is included. Water properties in liquid, vapor state and thermophysical properties of NAPL phase are calculated. The Henry's constant for air dissolution in aqueous and NAPL phase is assumed to be constant (Falta et al., 1995).

The thermophysical and transport properties of NAPL or organic chemical computed using very general equation of state which is based on critical properties. The integral finite difference method is used for spatial discretization (Narasimhan and Witherspoon, 1976). One, two or three dimensional anisotropic, heterogeneous porous media or fractured system is applied (Falta et al., 1995). In a nonisothermal system, governing equation consists of three mass components, three mass balance

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equations and one energy balance equation. The balance equation can be written as (Falta *et al.*, 1995):

$$\frac{d}{dt} \int_{V_n} \overbrace{M_K}^{\substack{mass \\ accumulation \\ term}} dV_n = \int_{\Gamma_n} \overbrace{F_K}^{flux\ term} \cdot n d\Gamma_n + \int_{V_n} \overbrace{q_K}^{\substack{sink\ and \\ source\ term}} dV_n \quad (1)$$

K   =    w:water, a:air, c:chemical or h:heat
$V_n$   =    arbitrary flow region
$\Gamma_n$   =    surface area
n   =    inward unit normal vector
$M_K$   =    mass of component K
$F_K$   =    mass flux of component K
$q_K$   =    rate of mass generation of component K

**Simulation process of DNAPL migration and remediation**

Before the simulation can be run, the input parameter data is gathered and arranged according to the input data format (Falta *et al.*, 1995). The first step of simulation is to generate gravity-capillary equilibrium from initial conditions of fully saturation and no PCE present. The simulation is initiated by creating geometry model mesh for 2-D heterogeneous saturated porous media adapted from experiment by Ramsburg *et al.* (2004) as shown in Figure-1. The mesh contains 126 elements and 229 connections with the grid increment of 0.05m for grid direction x-axis (NX) and z-axis (NZ). The grid increment for grid direction y-axis (NY) is 0.014m. The soil used in this study is fine sand and coarse sand.
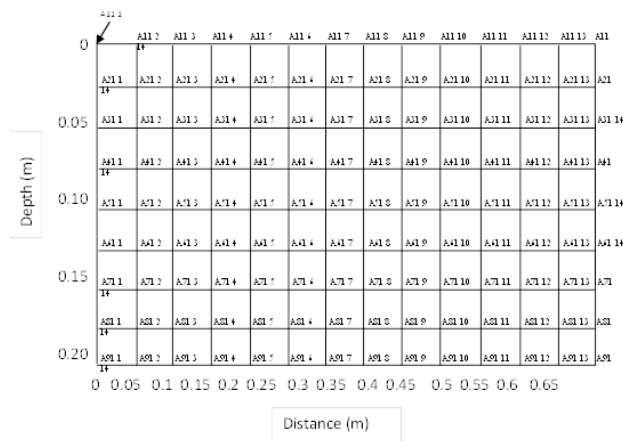


**Figure-1.** Mesh diagram of 2-D heterogeneous saturated porous media model adapted from experiment by Ramsburg *et al.* (2004).

The number of mass components is 2 for aqueous and air and equal to the number of balance equations. The number of phases is 3 for solid phase, aqueous phase and air phase. After 20 time steps, the simulation has reached a

rather accurate static equilibrium. The capillary pressure between gas phase and DNAPL is neglected.

In the second simulation, total volume of 27ml PCE is injected at the distance of 0.05m from top center element (A21 8) at a rate of $2.7 \times 10^{-5}$ kg/s for a period of 1620 s (27 min). The purpose of injected PCE below 0.05m fine sand is to minimize PCE backflow same as the experiment method. The specific enthalpy of the injected PCE is $3.8 \times 10^4$ J/kg corresponds to liquid PCE at a temperature of 22 °C. The number of mass component and number of balance equations are equal to 3 to be able to represent PCE. The initial conditions are the conditions at the end of the previous simulation. The contour plot of liquid PCE phase saturation distribution after 1620 s is shown graphically in Figure 2. The value of PCE saturation ranged from 0.01 to 0.36. The migration of PCE is downward direction up to 0.2 m and laterally direction for a distance of 0.3 m. The PCE saturation distribution area is approximately 0.06 $m^2$.
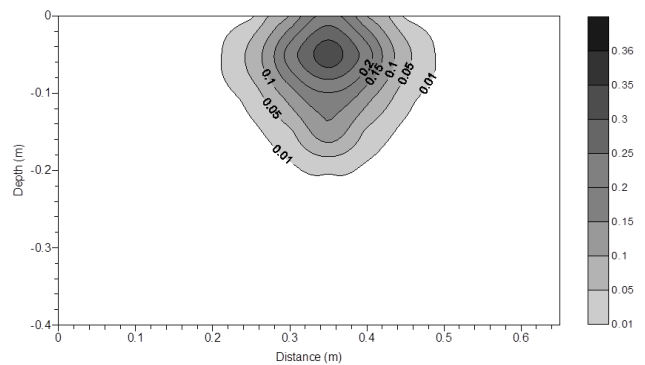


**Figure-2.** The contour plot of PCE phase saturation distribution after 27 min of PCE injection.
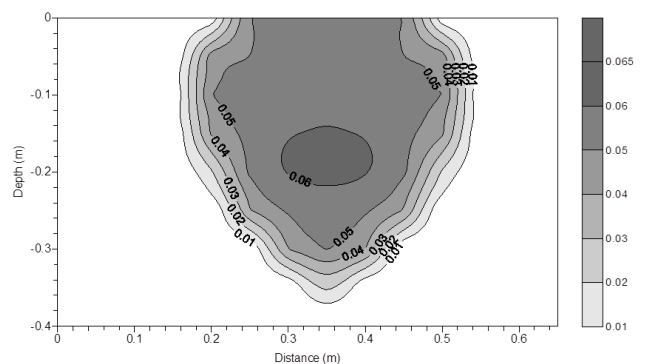


**Figure-3.** The contour plot of PCE phase saturation distribution after 24 hours of PCE redistribution.

In the third simulation, the previously injected PCE is simply allowed to redistribute itself. No additional fluids are injected. The initial conditions are the conditions at the end of the previous simulation. This part of simulation is run for a period of 86,400 s (24 hours). The output data is shown in Appendix I. The contour plot of liquid PCE phase saturation distribution after 86, 400 s is

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shown graphically in Figure-3. The value of PCE saturation ranged from 0.01 to 0. 065. The migration of PCE is downward direction up to 0.37m and laterally direction for a distance of 0.38 m. The PCE saturation distribution area is approximately 0.1406 m$^2$. The high saturation PCE has spread to more distance with low saturation of PCE. The low permeability of fine sand at center of model shows no affect the PCE migration.

In the final step of simulation, steam with a specific enthalpy of 2.676 x 10$^6$ J/kg is injected at the distance of 0.05 m from left boundary and 0.10 m from bottom boundary (element A71 2) and at right boundary and 0.10 m from bottom boundary (element A71 14). The steam is injected at a rate of 1.0 x 10$^{-4}$ kg/s for a period of 70 min. The deliverability boundary conditions are used at the right of 2-D model to represent extraction well. The deliverability boundary conditions are specified in block GENER. The initial conditions are the conditions at the end of the previous simulation. The number of balance equations is increased to 4 to include energy balance equation. This final part of simulation is repeated for steam injection rate of 8.0 x 10$^{-5}$ kg/s, 6.0 x 10$^{-5}$ kg/s and 6.0 x 10$^{-5}$ kg/s for a period of 90 min, 130 min and 200 min respectively.

**RESULTS**

The numerical results for PCE removal using different steam injection and the temperature distribution was visualized by contour plot for a certain time. The details of total PCE injected, total PCE removed, percentage PCE removal and total remediation time is tabulated and compared with experiment results using surfactant-enhanced method by Ramsburg *et al.* (2004). The results were discussed according to theory of steam-enhanced extraction and the dominant mechanisms of PCE removal were identified.

Figure-4 shows the simulation results for concentration of total PCE removed over remediation time using steam-enhanced extraction method compared to past experiment by Ramsburg *et al.* (2004) using surfactant-enhanced method. The results show time taken to remove PCE using steam-enhanced extraction method is four times lesser compared to surfactant-enhanced method? PCE completely removed using steam-enhanced extraction method for a period of 4 hour. Surfactant-enhanced method had just start to removed PCE at a time of 4 hour after remediation process started and continues until almost completely removed after 20 hours. The total maximum PCE removed at a time ranged from 13 g/L to 25 g/L for steam-enhanced extraction method. The total maximum PCE removed at a time for surfactant-enhanced method approached 50 g/L due to in situ emulsification of PCE.

Figures 5 and 6 shows PCE maximum density and PCE minimum density over remediation time during steam-enhanced extraction respectively. The PCE density value ranged from approximately 1.62 g/ml to 1.5 g/ml. Compared to Ramsburg *et al.* (2004), the PCE density

ranged from 1.031 g/ml to 0.970 g/ml. The surfactant-enhanced method used by Ramsburg *et al.* (2004) has modified PCE density approximately to water density in order to reduce downward migration.
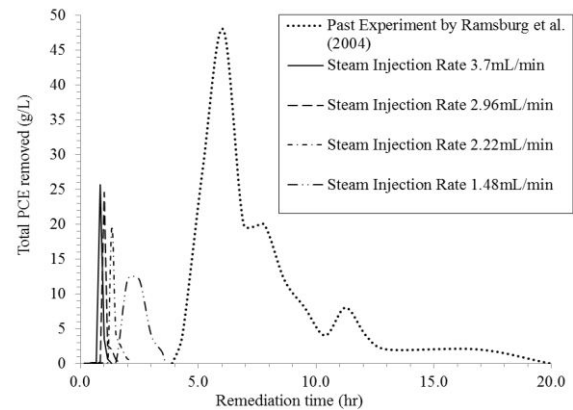


**Figure-4.** Simulation results for concentration of total PCE removed over remediation time using steam-enhanced extraction method compared to past experiment by Ramsburg *et al.* (2004).
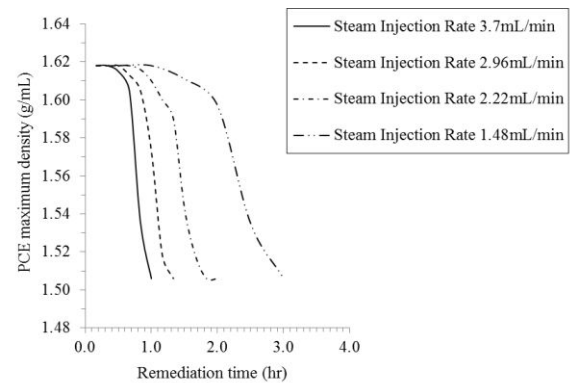


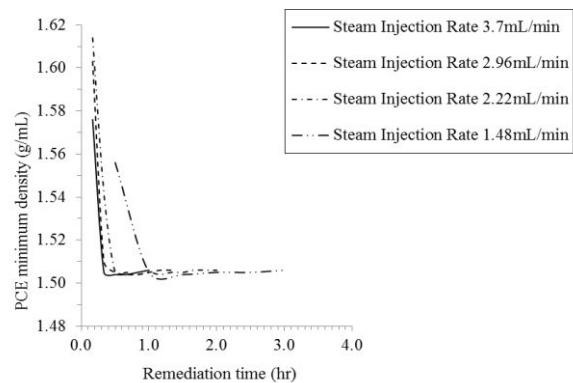**Figure-5.** PCE maximum density over remediation time during steam-enhanced extraction.



**Figure-6.** PCE minimum density over remediation time during steam-enhanced extraction.

Figures 7 and 8 shows PCE maximum viscosity and PCE minimum viscosity over remediation time during steam-enhanced extraction respectively. The PCE viscosities value ranged from approximately 0.9 cP to 0.3 cP. Compared to Ramsburg *et al.* (2004), the PCE viscosity ranged from 6.7 cP to 12.5 cP which are relatively high.
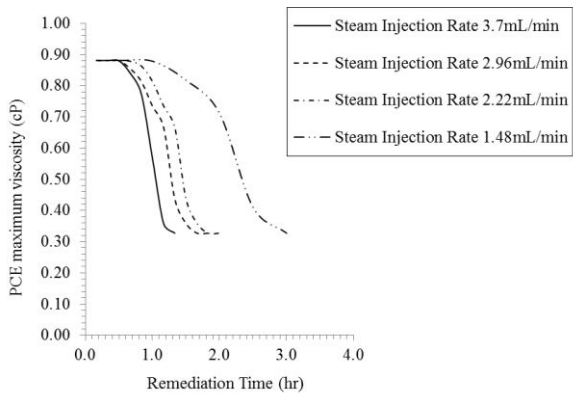


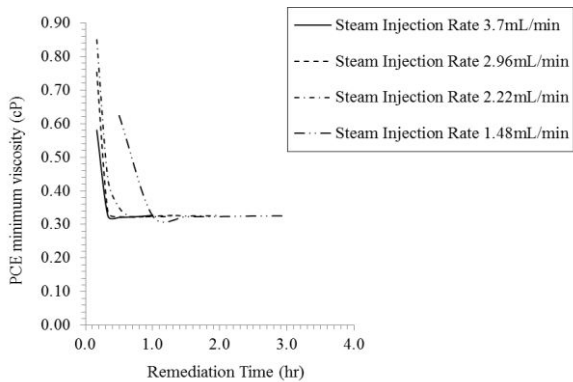**Figure-7.** PCE maximum density over remediation time during steam-enhanced extraction.



**Figure-8.** PCE minimum density over remediation time during steam-enhanced extraction.

Figure-9 shows numerical results for injection rate 1.0 x $10^{-4}$ kg/s at interval 10, 20, 30, 40, 50 and 60 minutes. At 10 min, steam front reach 0.15m distance and does not reach DNAPL area. At 20 min, steam front reach DNAPL area and start to give its latent heat of vaporization. The physical displacement of DNAPL is initiated. At 30 min, steam front has successfully push DNAPL towards extraction well. However, at 0.1m bottom 2-D model have shown that steam has slightly effect the DNAPL removal due to variable temperature. At 40 min, the DNAPL has successfully pushed up to distance 0.5m as steam front reach distance 0.5m.

However, at 0.1m bottom 2-D model have shown the DNAPL movement is slow. At 50 min, top DNAPL area are completely removed except at bottom 0.1m which shown the DNAPL is at 0.15m from extraction well. At 60 min, the DNAPL is at 0.05m from extraction well. At 70

min, DNAPL is completely removed and entire model is at steam temperature except at distance 0.1m from bottom is at variable temperature.



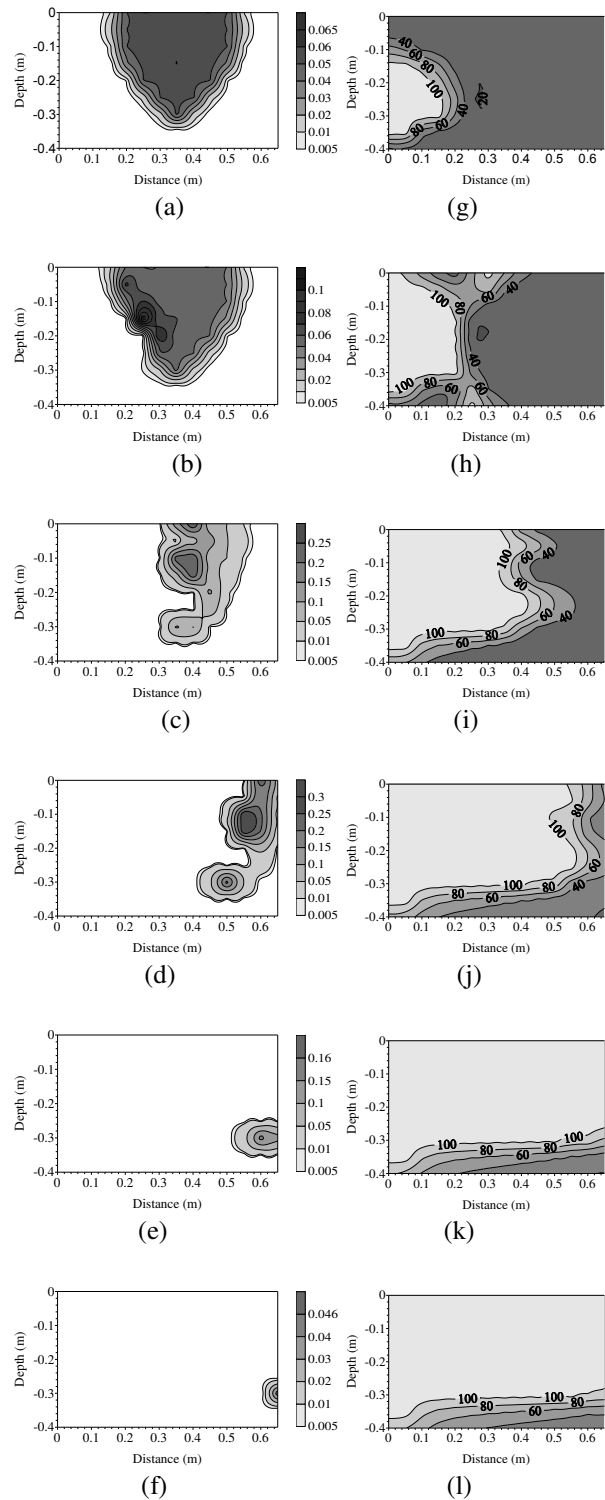**Figure-9.** Numerical results for PCE removal using steam-enhanced extraction with injection rate 1.0 x $10^{-4}$ kg/s: (a-f) PCE saturation distribution and (g-l) temperature distribution (°C) after 10 min, 20 min, 30 min, 40 min, 50 min and 60 min.

Table-1 shows the PCE removal for steam-enhanced extraction method and past experiment by Ramsburg *et al.* (2004). High PCE removal was obtained with less remediation time using steam-enhanced extraction method for steam injection rate 1.0 x 10⁻⁴ kg/s indicating the efficiency of steam-enhanced extraction method.

**Table-1.** PCE removal for steam-enhanced extraction method and past experiment by Ramsburg *et al.* (2004).

| Parameter | Past Experiment by Ramsburg *et al. (2004)* | Steam injection rate for steam-enhanced extraction method (x $10^{-5}$ kg/s) | | | |
|---|---|---|---|---|---|
| | | **10.0** | **8.0** | **6.0** | **4.0** |
| Total PCE mass injected (g) | 44.3 | 44.3 | | | |
| Total PCE removed (g) | 40.49 | 44.3 | 44.29 | | |
| Percentage PCE removal (%) | 91.4 | 100 | 99.99 | | |
| Total remediation time | 20 hour | 1hour10 min | 1hour30min | 2hour 10min | 3hour 20min |

## DISCUSSIONS

By using steam-extraction enhanced method in remediation of PCE from saturated heterogeneous porous media, it was found that physical displacement by continuous vaporization and co-boiling process is the dominant mechanism of PCE removal. In the initial injection of steam, when steam is injected into the 2-D model, latent heat of vaporization from steam was transfer into the heterogeneous porous media. Once steam loses heat due to the heat transfer, steam condenses into aqueous phase with high temperature and moves outward into soil, displace air and water.

Steam injection into the 2-D model was continued until the ambient soil temperature reach steam temperature. This causes the high temperature aqueous phase around the soil to create more steam which was called as a steam front. These steam fronts start to propagate away from the steam-temperature soil area into the nearby variable temperature soil area and ambient temperature soil area. The constant movement of steam propagation causes the variable temperature of aqueous phase forcing the ambient temperature of air and water to move. The constant movement of steam propagation is cause by steam pressure and this process is called moving front. This process can be seen in Figure-9.

When the moving front process area reaches PCE contamination area, it will first reduce the PCE viscosity due to variable temperature of aqueous phase. Then when the steam phase arrived, it will vaporize the residual saturation of PCE and PCE that adsorbed in soil. This PCE-steam vapor phase will move to variable temperature area and ambient temperature area then condenses into PCE-aqueous phase. The accumulation of PCE-aqueous phase is called PCE condensate bank and the process is called steam stripping, another main mechanism of PCE removal. The continuous process of moving front minimizes the tendency of PCE condensate bank to migrate downward.

Steam distillation occurs when PCE boiling point increased with low temperature compared to normal boiling point with high temperature due to present of steam (water vapor). Thus, result in increased PCE to change its state to gas phase faster than normal distillation. This process occurs because PCE is immiscible in water. With the present of water, the PCE boiling points reach early when total vapor pressure of the system equal to one atmosphere compared to when total vapor pressure of individual component (PCE without present of water) equal to one atmosphere.

Steam injection rate is one of the most important design considerations for steam-enhanced extraction. The greater the steam injection rate, the greater the heating rate of subsurface, greater recoveries and greater energy efficiency. The greater the injection rate will reduce total time required to remove PCE. As seen in Figure-4, the remediation time directly related to steam injection rate. The total time required in removing PCE using steam injection rate 1.0 x 10⁻⁴ kg/s, 8.0 x 10⁻⁵ kg/s, 6.0 x 10⁻⁵ kg/s and 4.0 x 10⁻⁵ kg/s is 70 min, 90 min, 130 min and 200 min respectively. Even though the difference between each injection rate is 2.0 x 10⁻⁵ kg/s, there are significant impacts in the difference in remediation time with the increment approximately 20 min, 40 min and 70 min.

The position of steam injection and extraction well plays an important role to the efficiency of surfactant-enhanced extraction. From Figure-9, the bottom PCE saturation removal is slow compared to top PCE saturation removal. This is due to the steam propagation area from steam injection point shown that the heating area slightly reach bottom area. Steam area was propagating at top but variable temperature at bottom which does not reach steam temperature.

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The simulation results of steam-enhanced extraction for PCE removal was compared with surfactant-enhanced method implemented by Ramsburg *et al.* (2004). Ramsburg *et al.* (2004) use the macroemulsion solution and low-IFT displacement solution in order to minimize downward migration of PCE during surfactant-enhanced method. However, the time taken to remove PCE from the 2-D model using surfactant-enhanced method was longer than using steam-enhanced extraction. The time taken to remediate PCE using steam-enhanced extraction is four time lesser compared to surfactant-enhanced method by Ramsburg *et al.* (2004) as shown in Figure-4. Therefore, the reduction in remediation time will lead to reduction in total overall cost and time. The use of steam-enhanced extraction method to remove PCE from heterogeneous porous media of fine sand and coarse sand is more efficiency than surfactant-enhanced method by Ramsburg *et al.* (2004).

The DNAPL removal distributions for each injection rate have the same pattern during steam-enhanced surfactant implementation. However, the difference is in terms of remediation time as shown in Table-1. The PCE density value range from 1.5 g/ml to 1.62 g/ml. Steam-enhanced extraction only slightly affect the PCE density value as shown in Figure 5 and 6. The PCE viscosities value range from 0.3 cP to 0.9 cP as shown in Figure 7 and 8. Viscosity drops rapidly with temperature thus is an influence factor in PCE removal.

The DNAPL removal can be achieved by physical displacement through volatilization, evaporation and/or steam distillation (Stewart and Udell, 1988). Steam distillation and steam stripping are the main recovery mechanisms which cause the formation of DNAPL bank. Laboratory experiment has shown that pure, separate, liquid-contaminants with lesser boiling point compared to water leaves only a small amount of contaminants which adsorbed in soil during remediation (Hunt *et al.*, 1988). Combination of water and contaminants contribute to the total vapor pressure. Boiling point reach at lower temperature than normal boiling point for individual component (Atkins, 1998). Many researchers have found that steam-enhanced extraction performance influenced by heating rates which more related to steam properties and steam injection rates (Baker, 1969; Cook, 1995; Myhill and Stegemeier, 1978).

Several researchers have found temperature is directly related to oil residual saturation. By increasing the temperature will reduce the oil residual saturation (Davis and Lien, 1993; Edmondson, 1965 Poston *et al.*, 1970). Greater recovery allow by enhancement of liquid and adsorbed contaminants volatilization is the result of greater vapor pressure due to higher temperature within the interfacial effects limit (Lingineni and Dhir, 1992). Co-boiling is an important mechanism in DNAPL removal due to stripping effect by the phase change (Heron *et al.*, 2005; Heron *et al.*, 2009; Udell, 1998).

## CONCLUSIONS

This 2-D simulation has been conducted to achieve objective (1) to simulate the migration and removal of DNAPL from saturated heterogeneous porous media in 2-D model, objective (2) to identify the dominant mechanisms of DNAPL removal and objective (3) to evaluate the performance and efficiency of steam-enhanced extraction during DNAPL removal. Objective (1) is achieved by running the simulation program for PCE migration and removal from 2-D saturated heterogeneous porous media using T2VOC TOUGH2. Objective (2) is achieved by identifying the dominant mechanism of DNAPL removal as a result from steam-enhanced extraction remediation process. Objective (3) is achieved by comparison of percentage successful DNAPL removal, time taken to remediate DNAPL and comparison with surfactant-enhanced method by Ramsburg *et al.* (2004) as a function to evaluate the performance and efficiency of steam-enhanced extraction.

Steam-enhanced extraction simulation was performed in a 2-D saturated heterogeneous porous media contaminated with PCE. The PCE was injected at top center of 2-D media and redistribute itself. Four different injection rates were selected and were injected at bottom left of 2-D media to analyze the efficiency of steam-enhanced extraction method in PCE remediation process. The PCE was extracted at extraction well during the remediation process at right side of 2-D media. The PCE distribution saturation and temperature distribution was visualized during the simulation.

The results shows that increased in steam injection rate will increase the PCE remediation time. The DNAPL is 100% removal with steam injection rate $1.0 \times 10^{-4}$ kg/s, 99.99% removal for $8.0 \times 10^{-5}$ kg/s, $61.0 \times 10^{-5}$ kg/s and $4.0 \times 10^{-5}$ kg/s with remediation time of 70 min, 90 min, 130 min and 200 min respectively. There are significant impacts in the difference in remediation time with the increment approximately 20 min, 40 min and 70 min with the same increment of steam injection rate. The dominant mechanisms of PCE removal is physical displacement by vaporization and co-boiling enhanced by steam distillation and steam stripping process.

The simulation results of steam-enhanced extraction for PCE removal was compared with surfactant-enhanced method implemented by Ramsburg *et al.* (2004). It was discovered that the time required to remove PCE using steam-enhanced extraction is four times faster than the time required to remove PCE using surfactant-enhanced method. This shows the capability of steam-enhanced extraction to recover contaminant effectively.

Steam-enhanced extraction has a greatest potential to decrease clean-up time which will offset greater capitol cost of the system. Steam-enhanced extraction do not required excavation and potential contaminants are not injected to subsurface. The accelerated removal rates will reduced remediation time and thus reduce overall operating cost. In addition, the critical information such as site characterization and

operation system design is important to effectively apply steam-enhanced extraction.

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