Experimental investigation on light non-aqueous phase liquids removal from groundwater using steam injection technique

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Abstract. Groundwater pollution by Non-Aqueous Phase Liquids (NAPLs) has become an increasing threat. This article studied the steam injection efficiency in the groundwater remediation contaminated with non-aqueous phase liquid (diesel) through a bench-scale laboratory experiment. The experimental set up consists of a steam boiler and sandbox. Steam, which was generated from the steam boiler was supplied to the sandbox at injection rate of 0.14 m³/s, pressure of 1.5 bar and temperature of 150°C. The initial volume of diesel used was 500 ml. At the supply of the steam to the sandbox, it was observed that the mixture of groundwater and diesel was heated and at a temperature above their boiling points, the mixture change phase and vaporized from the chamber through the outlet or recovery side into the condenser and were separated on cooling using phase separator. The remediation time was from 0 to 6 hours and it was showed that as the time increases, the recovered volume of diesel increases as 66.04% of diesel was recovered after the allowed 6 hours. Therefore, it was evident that the steam injection technique is efficient in the removal of light non-aqueous phase liquids in groundwater.

1. Introduction

Water is one of the most important resources to maintain a living planet and the main part of our drinking water is gained by the extraction of groundwater out of aquifers in the subsurface. However, aquifers are sometimes endangered by contaminations caused by industrial wastes or accidents, which release hazardous substances into the environment [1]. High potential ecological and health risk are demonstrated by the existence of contaminants at concentration above background level in groundwater [2]. Among pollutants that directly affect humans and animals is hydrocarbon, contaminating groundwater resources causing serious pollution problem. Therefore, to decrease the concentration level or completely remove the compounds is a challenging issue. Consequently, due to the rising population of the world, there is a significant rise in water consumption. Thus, it is important to conserve the quantity and quality of the groundwater supply.

Petroleum industry originally develop the steam injection to increase oil recovery from the ground repositories [3]. Nowadays, steam injection is been used as a remediation technique for chlorinated solvents in the subsoil, enhancing soil vapour extraction. Taking advantage of the heat capacity of...
steam to achieve a higher heat input than hot air, for example, providing dissolution, vaporization and mobilization of contaminants and thereby a more efficient recovery. Separate, pure liquid-phase contaminant with a boiling point below 100°C has been shown by experiment to be removed completely from steam zone except the minute amount dissolved in liquid water or adsorbed to solid surfaces which are likely present in the steam zone [4].

Laboratory studies by [5] showed that in fine soils, steam injection remediation is achieved at a slower rate when compared with coarse soils. Also shown by the experiment is the contaminant lower recovery efficiency of poorly sorted soils when injected with steam. The effect is partly due to poorly sorted or fine-grained soils lower permeability leading to bigger residue saturation, and lower rate of injection at a particular injection pressure. With sand grain sizes at a particular range, uniform contaminant recoveries were attained, but a decrease in the grain size required more treatment times for the same recovery to be achieved. A further decrease in the grain size the recovery efficiency also declines.

It was inferred by many researchers that steam injection recovery is closely related to heating rates [6, 7]. However, the dependencies are more related to the injection rates and steam properties. This dependence is more related to steam properties and injection rates. Recovery achieved by steam injection is affected by the thermal properties of the soils [5; 8]. The soil target zone thickness is a property that may significantly affect the treatment process of the soil. During steam injection process, injected heat lost to overlying and underlying strata is inevitable. The percentage of injected heat staying within the target zone is directly proportional to the thickness of the zone.

Based on theoretical studies, it was predicted that liquid hydrocarbons with boiling temperature within 175°C may be removed completely behind steam condensation front under certain conditions [9; 10]. One-dimensional column experiment supports the conclusion by showing the complete elimination of gasoline and toluene [4] and 96.8 to 99.8 percent recovery of No. 2 fuel oil and jet fuel [5] by steam injection. This research investigates experimentally, the efficiency of steam injection in the remediation of groundwater.

2. Methodology
The set up consists of steam injection mechanism to remediate contaminated groundwater polluted with NAPL (diesel). It consists of two parts, which are;

a. The steam boiler: It consists of heating element, a cylinder containing the water, a blower (fan) to aid the heating element, ash tray to collect ash residue from coal burning, relief valve, a pressure gauge to determine pressure value and temperature recorder. The heat that was generated by the combustion of charcoal was transferred to the water in the cylinder to generate steam.

b. The test chamber or sandbox: It was made of steel to withstand high heat supplied to it. The outside was insulated to prevent heat loss from within the chamber using fiber materials inside the space. Part of the front view of the test chamber was cut and was fixed with glass to allow visual inspection of the inside of the chamber. On the upper section of the left hand side of the chamber was the injection port for allowing the generated steam from the steam boiler into the test chamber or sandbox. The chamber right hand side has the extraction port, used for the collection of vaporized gas into the phase separator through the condenser. Phase separator was used to separate water from the condensed gases.

2.1. Experimental Procedure
The laboratory experiment was conducted in a three-dimensional test chamber (sandbox) as shown in Figure 1. The contaminant considered for this work was diesel. Diesel is a mixture of hydrocarbons with boiling points in the range of 150°C - 380°C obtained from petroleum. It is able to float on water due to its lightness when compared with water, it’s referred to light non-aqueous liquid (LNAPL). In the course of this experiment, two variables: the injection rate of the steam and contaminant initial
concentration (measured by initial volume) were investigated. The test chamber of the dimension 118 x 8.5 x 58cm was packed uniformly with a layer of dried coarse sand up to a level of 21cm. An amount of 6cm layer of stone was packed to cover the surface of the coarse sand. This prevents the mixing of sand with the water in the sandbox. Then, non-contaminated water was introduced into the test chamber. 500ml of the contaminant was measured by using measuring cylinder. This was the initial volume of the contaminant \( (V_1) \) used. The measured contaminant was then introduced into the test chamber (sandbox) to contaminate the water in the test chamber. By using a tap to control the flow rate, the generated steam through the injection port was allowed to the test chamber. The flow rate was determined through the flow meter incorporated at the steam boiler outlet.

As the contaminated water is being heated, the temperature at different time intervals was measured using a digital thermometer. Vaporization of the contaminant started when its boiling point was reached. The effluent gas was collected into the phase separator at an interval of 1 hour through the condenser by opening the extraction port. To allow separation of water from recovered contaminants, the condensate was cooled. This volume recovered after the separation of the water is been measured at an interval of one-hour time. The final recovered volume of contaminant, which is the required result of the experiment, was measured through a measuring cylinder so as to know the final volume of the contaminant \( (V_2) \). The whole procedure was repeated until there is no recovery from the extraction point showing the complete removal of the contaminant.

\[ \text{Figure 1: Experimental setup schematic diagram} \]

### 2.2. Determining recovery efficiency

The effectiveness of the steam injection technique in remediating groundwater using contaminated water sample was determined through the recovery efficiency. Recovery efficiency was determined as the ratio of the final volume of contaminant recovered after the experiment to the initial volume of contaminant introduced to the test chamber.
\[ Recovery \text{ efficiency} = \frac{V_2}{V_1} \times 100\% \]  

\( V_1 \) represents the initial volume of contaminant introduced (ml) and \( V_2 \) represent the final volume of contaminant recovered (ml).

3. Results

A zone was created by steam injection with the steam temperature in the coarse sand layer upper part having convection as dominant heat transfer process. At the extraction side, stream broke through after steam injection for few minutes. During this time, steady-state was reached by the steam zone and further heating of the porous media was because of condensate flow and conduction. The experimental results for the removal of diesel from groundwater using steam injection with the volume of the pollutant (diesel) measured as 500ml at the experiment commencement; steam injection rate of 0.14m³/s, pressure of 1.5bar and temperature of 150°C were reported in table 1.

Table 2 gives the values of recovery efficiency with their corresponding time allowed for remediation as calculated from the experimental results. The graph and bar chart of the recovery efficiency of diesel against remediation time were shown in Figure 2 and Figure 3 respectively. Separate phase diesel appears in the condenser after approximately 35 minutes, and 66.04% of the initially introduced volume was recovered within the next 6 hours. Measurement uncertainties during recovery, loss during emplacement are responsible for unaccounted volumes. At the experiment termination, with the box total volume heated to steam temperature, any diesel isn’t expected to remain in the sandbox.

| S/N | Time(hours) | Recovery (ml) |
|-----|-------------|---------------|
| 1   | 0           | 0             |
| 2   | 1           | 98.10         |
| 3   | 2           | 152.15        |
| 4   | 3           | 220.00        |
| 5   | 4           | 291.75        |
| 6   | 5           | 311.20        |
| 7   | 6           | 330.04        |

Table 2: Results of groundwater remediation using steam injection showing values of recovery efficiency determined from experimental results obtained.

| S/N | Time(hours) | Recovery (ml) |
|-----|-------------|---------------|
| 1   | 0           | 0             |
| 2   | 1           | 98.10         |
| 3   | 2           | 152.15        |
| 4   | 3           | 220.00        |
| 5   | 4           | 291.75        |
| 6   | 5           | 311.20        |
| 7   | 6           | 330.04        |
4. Discussion

The experiment was used to determine recovery efficiency of diesel in groundwater with steam injection rate of 0.14m³/s, pressure of 1.5bar and temperature of 150°C. The results of the recovered diesel were taken at every 1-hour interval up to 6 hours. The results obtained showed that as the remediation time increases from 0 hours to 6 hours, the recovered volume of diesel increases until the final recovery efficiency of diesel recovered was 66.04% at 6 hours. The remaining part of diesel unaccounted for or not recovered was due to losses during the recovery, adsorption of diesel particles to the solid surface of the test chamber, and measurement uncertainties.

It was recorded that as the remediation time increases, the contaminant (diesel) recovery also increases until the final recovery efficiency of 66.04% was obtained using steam injection; this implies that the recovery is a function of time.

5. Conclusion

Steam injection experimental investigation was performed in a sandbox with dimensions of 118 x 8.5 x 58 cm to remediate diesel present at a different phase above the water level in the sandbox. Steam was injected at the rate of 0.14m³/s, pressure of 1.5bar and temperature of 150°C. The experimental investigation was performed to determine the recovery efficiency of diesel through a bench-scale laboratory experiment using steam injection.

The recovery efficiency calculated from the experimental result using steam injection to remediate diesel from groundwater was found to be 66.04%. This shows that steam injection is efficient in the remediation of NAPLs from groundwater. Therefore, the steam injection can be used for effective remediation of NAPLs from groundwater to reduce the potential environmental problems and health infectious diseases associated with groundwater pollution.
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Conflict of Interests

The authors declare that there is no conflict of interest.

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