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Impact of Magnetic Fields on the Efficiency of Dense Non-Aqueous Phase Liquid Removal from Unsaturated Zones Using Steam Injection

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Unsaturated zone is of great importance in providing water and nutrients that are vital to the biosphere and the main factor controlling water movement from the land surface to the aquifer. Contamination of unsaturated zone by Dense Non-Aqueous Phase Liquids (NAPLs) has becoming major threat to human environment as a result of increasing concern with industrialization. The use of steam injection for remediation of porous media which are contaminated by DNAPLs has not

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given the desire recovery efficiency, hence the need for improvement in recovery efficiency has been a subject of continuous study. This study investigated the effect of magnetic field on the removal of DNAPL from unsaturated zone using steam injection.
An unsaturated zone of a sand box of interior dimensions 110 x 74 x 8.5 cm was polluted at different periods with 200 ml of Carbon tetrachloride. Steam injection experiment with flow rate of 0.01 m^3/s was performed to determine the recovery efficiencies of Carbon tetrachloride in an unsaturated zone containing sand of porosity 0.42 and permeability of 0.001163779 cm/s. Magnetic field in step of 1 Tesla (T) was introduced from 1-3 Tesla (T) into experiment. The effects of magnetic field on removal of DNAPL from unsaturated zone using steam injection only and steam injection with magnetic field were compared using descriptive statistic.
The recovery efficiency of Carbon tetrachloride using steam injection only was 82.05 %, while that with varying magnetic field at 1T, 2T and 3T were 89.45%, 94.95% and 95.35% respectively. The recovery efficiency of steam injection with varying magnetic field at 1T, 2T and 3T were 9.02, 15.72, 16.21% higher than the result of steam injection only for Carbon tetrachloride.
The result demonstrated the ability of steam injection to recover contaminants from the subsurface. The application of magnetic field as an aid to facilitate system activities has been signifi-cantly effective due to its ability to overcome the constraints of conventional treatment processes. A combined application of steam injection with magnetic field appreciably enhances the removal of Non Aqueous phase liquids from Unsaturated Zone.

Keywords: Magnetic field; dense non aqueous phase liquid; unsaturated zone; steam injection.

1. INTRODUCTION

Water is the key to food security. Crops and livestock need water to grow. Agriculture requires large quantities of water for irrigation and of good quality for various production processes. *Water has a major and fundamental role in safety of food production*. It is a critical resource for the food industry with wide uses. *Water is needed for food hygiene*, particularly cleaning fruits and vegetables. Washing foods with clean water can remove harmful pesticides or residual. Groundwater is one of the most important natural resources to man. It provides thirty-six percent (36%) portable water for domestic, forty-two percent (42%) for industrial use, and twenty-four percent (24%) for agriculture/irrigation especially in a place where there *is* no surface water like an arid region. It is found below the surface of the earth in the soil pore space and cracks of rock formation. These units of rock are called aquifer [1].

The groundwater can be contaminated in different ways by the different sources which natural sources, septic systems, improper disposal of hazardous waste, landfill and. impoundments, sewers, pipelines, pesticides/fertilizers use, drainage wells, injection wells/floor drains, improperly constructed wells, improperly abandoned wells, active drinking water supply wells, poorly constructed irrigation wells, mining activities, and spills from stored chemicals and petroleum product such as Non-Aqueous Phase Liquids [2].

Non-Aqueous Phase Liquids (NAPLs) are liquids contaminants solution that does not dissolve in or easily mix with water, they contaminate soil and groundwater. It is classified into Dense Non-Aqueous Phase Liquids (DNAPLs) and Light Non-Aqueous Phase Liquids [3]. Effects of groundwater contamination results range from reduced drinking, agriculture, industrial water qualities, loss of water supply, degraded surface water system, destruction of aquatic habitats, higher cleanup costs, high costs for alternative water supplies, and health problems such as kidney failure and cancer which are life-threatening disease [4; 5].

Groundwater remediation is the process that is used to treat polluted soil and groundwater by removing the pollutants or converting them into harmless substances. During the past few years, several in situ techniques have been developed for clean up of soils contaminated by NAPLs. Existing remediation technologies include vapour extraction, radio frequency heating steam, stripping (steam injection) and biological/chemical/physical methods. Thermal technology, which make use the application of heat to the groundwater via soil to increase the recovery efficiency of volatile and semi-volatile contaminants from the aquifer. Thermal treatment includes the use of electrical resistivity heating, steam enhanced extraction, conductive heating, radio-frequency heating, and vitrification technologies [6].

Among these various in situ technologies, steam injection is being investigated as a potential method for remediation of NAPL contaminated soils. Some for the knowledge and techniques developed in petroleum engineering for enhanced oil recovery by steam injection are useful to the problem of steam stripping for remediation of NAPL contaminated soils. In enhanced oil recovery, the objective is to remove the maximum amount of oil from the reservoir as long as it is economically feasible while small amounts of oil left in the formation are usually ignored. In contrast, the purpose of remediation efforts is to remove as much of the contaminants as possible until clean up levels are achieved. Steam injection has been applied at some sites in the USA [7]. It has been applied in unsaturated as well as saturated zones and is generally more efficient in porous media such as sand than in low permeable soils [8].

Magnetic field is a region or space or a vector around a bar magnet where the effect of magnetic force can be experienced of felt. Several researches has proved that, the magnetic force is capable of improve remediation of NAPLs from both saturated and unsaturated zone using steam injection by reducing the rate of migration of NAPL in a porous media. Magnetism has a unique physical property that independently helps in water purification by influencing the physical properties of contaminants in water. In addition, its combination with other processes enables an improvised efficient purification technology. Imposition of an external magnetic field appreciably decrease pollutant spread in an aquifer. Subsequently cut down on remediation processes [9]. Magnetic field along the flowing path of NAPL can be used to get a powerful permanent magnet that is capable of breaking down the Van der waal’s force thereby molecular configuration and intermolecular force is reduced which can lead to increase in the rate of vaporization of NAPLs [10].

Many remediation technologies can be used to remediates groundwater.Appropriate remediation technology to be selected on-site depends on certain factors such as soil condition, properties of contaminants, the method, and types of soil contaminants and more so, there is no best particular method suitable for remediate all types of soil and groundwater contaminants [11]. Sometimes more than one remediation technology may be used which may be combined or arranged in parallel or series purposely to increase the remediation efficiency of contaminated soil and groundwater (treatment train). The effectiveness of this treatment train on certain site will depends on many factors which must be considered. Such factors includes the rate of spread of NAPL, feasibility of the technology and objective of remediation of the site which may be prevention of spread of pollutant, removing of contaminant from saturated or unsaturated zone, type of NAPLs to be removed weather it is LNAPL or DNAPL, as proposed aim of the remediation and this is called treatment train [12].

Though most of the remediation technology yields good results, there is need to improve their efficiency. Therefore, the aim of this research was to experiment Effects of Magnetic fields on the Removal of Dense Non-aqueous Phase Liquid from an Unsaturated Zone using Steam Injection.

2. METHODOLOGY

This research work involved the experimental investigation of the removal of Dense Non-aqueous phase liquid (DNAPL) from Unsaturated Zone using Steam Injection with Magnetic Effect. The pollutants used for the experiment was Carbon tetrachloride (DNAPL). The experiment was carried out at the New Fluid Mechanic Laboratory of the Mechanical Engineering department, LAUTECH, Ogbomoso, Oyo State.

2.1 Geo-Technical Test

Geo-technical test was performed on the soil sample (obtained in front of chemical engineering laboratory, LAUTECH premises) in order to determine the identity of the soil samples used in the experiment. This test was carried out in Geotechnical Engineering Laboratory in Civil Engineering Department of Ladoke Akintola University, Ogbomoso, Oyo state.

2.1.1 Soil porosity

Porosity is the amount of empty space in a soil and rocks. Porosity was calculated using equation 1 to 3 (New Jersey Department of Environmental Protection 2011).

$$\text{Macro-porosity} = \frac{Pore\ space\ volume\ of\ gravel}{Total\ volume} X\ 100 \quad (1)$$

Micro-porosity = $\frac{Pore\ space\ volume\ of\ sand}{Total\ volume} X100$ (2)

Total porosity = Macro-porosity + Micro porosity (3)

2.1.2 Soil permeability

The process was repeated until constant value was obtained and hydraulic conductivity was calculated using the equation (4): Soil Permeability was calculated using equation 4 (New Jersey Department of Environmental Protection 2011).

$$K_T=\frac{QL}{Ath} \quad (4)$$

Where: K_T = Hydraulic conductivity (cm/min) L =length of specimen in centimeters

t = time for discharge in minutes Q= volume of discharge in cm^3 (assume 1 mL = 1 cm^3)
A = cross-sectional area of permeameter (soil core) ($A = \frac{\pi}{4} D^2$, D is the inside diameter of the permeameter (soil core) h = hydraulic head difference across length L, in cm of water

2.1.3 Moisture content

Muhammed [13] used oven- drying method of English Standard Institution (E.S.I) part II-1973, to determine the moisture content of the soil sample. The moisture content was determined using Equation 5

$$M_{content}=\frac{M_2-M_3}{M_3-M_1} \times 100 \quad (5)$$

Where: M_1 = Weight of an empty clean container with lid (g) M_2 = Weight of clean container with lid + wet soil (g) M_3 = Weight of clean container with lid+ dry soil (g)

2.1.4 Soil texture

Soil textural determination was done using hydrometer method described by Bouyoucos method as described by Andres *et al*(2014).

$$\%Sand=\frac{Sample\ mass-40\ seconds\ reading}{Sample\ mass} \times 100 \quad (6)$$

$$\%Clay = \frac{Two\ hours\ reading}{Sample\ mass} \times 100 \quad (7)$$

$$\%Silt = (100\% - \%\ sand - \%\ clay) \quad (8)$$

2.2 Tools and Equipments

The followings are description of some of major tools and equipment that was used for the experiments:

2.2.1 Steam boiler

Steam boiler consists of an enclosed pressure vessel where water is being heated to produce steam through heat energy source. This steam boiler designed in such in a way that, it is capable of using either charcoal, cooking gas or electricity by 2KW electric heater as source of heat energy but gas was used of the work. The steam boiler is equip with digital temperature measuring device, pressure gauge, thermostat and pressure safety valve which are use for measuring steam temperature, pressure and control the internal pressure of the boiler respectively. It is also provided with fluid flow-meter to control and measure the flow rate of the steam leaving the steam boiler to the sand box. Plate 1 shows the picture of steam boiler that was used for the research.

2.2.2 Sand box

The experiment was conducted in a sand box. The sand box had the interior dimension of 110 X 74 X 8.5 cm (Fig. 3). The sand box was constructed from galvanized steel and a front glass panel. The glass panel was to allow for taking photographs, visual inspection and access to the sand packing. The sand box was lagged in order to minimized heat loss and loss of pollutant. Steam was injected into the sand box through the injection port. The steam from the steam boiler was super heated to 110 °C in order to ensure that the steam is a dry steam. The sand box was equipped with temperature sensor, pressure transducer and variable electromagnetic induction device to measure temperature, pressure and varies the magnetic field strength in the sand box respectively. Effluent gas (steam and pollutant) leave the sand box through the extraction port located at the opposite side inlet port of the sand box and was pass to the condenser.

2.2.3 Condenser

This is a device that was used to condense effluent vapour (steam and contaminant vapour) into a liquid state through cooling. The vapour was pass through a condenser which is made up of series of copper pipe coiled and submerged in a melting ice so that the latent heat of the vapor from the sand box is released and transferred to melt the ice. The condenser is also capable of using refrigerator system to condense the vapor when electricity is available but ice pack was used. It is fixed to the outlet (extraction port) port of the sand box. The condensate was collected and transfer to the phase separator.

2.2.4 Phase separator

Separating funnel was used as phase separator. It is a glassware use to separate the components of a mixture of two immiscible solvent phases (water and the contaminant) of different densities. This apparatus is like a funnel with a tap at the bottom of the funnel to drain a less dense liquid at the bottom of the funnel out while the denser one will remains and drain out later.

2.2.5 Electromagnetic device

An electromagnetic device was made up of coils of wires wound round a bar of iron or other ferromagnetic material. The principle of work is when electric current flows through the conductor (wire), it causes coils to generate magnetic field which has both magnetic north and south poles. This electromagnetic device was made up of 1.32 W DC electric motor from power sources of 0.32 A with frequency ranging between 3.75-6.75 HZ, rotational speed of 202.5 – 405 rpm. It is capable of generating variable magnetic field strength of 1-3 T which can be selected accordingly with help of switch and is capable of producing 3.63 Ncm torque.

2.3 Experimental Procedure for Removal NAPL from Unsaturated Zone Using Steam Injection

The sand box was filled up with sand to height level of 50 cm of which granite stone was filled up to 10cm from the bottom of the sand box. 200 mL of contaminant (Toluene and Carbon tetrachloride) was measured using measuring cylinder while the temperature of contaminant was cooled to 0 ^{O}C with ice parked around the container. This is to reduce the contaminant loss due to evaporation while pouring into the sand in the box. To make the experiments to be uniform, the same volume of contaminant was used throughout the experiment. Prior to the commencement of the experiments, the ambient temperature and original temperature of the sand in a sand box was measured using digital thermometer.

Steam at 1.2 bar pressure and temperature 120 °C was injected into the sand box from the injection port located at the 40 cm from the bottom side directly opposite to extraction port located at the side of the other side of the sand box at a constant steam flow rate of 0.01m^3/s measure using flow meter which was control manually by flow valve as used by Adegbola *et al* [14]. With the help of automatic temperature control of the boiler and pressure relieve valve coupled with the expected high permeability of the soil, the injection pressure was a little bit above atmospheric pressure which was measured by pressure gauge on the sand box. Steam injected into the sand box and vapor of the contaminants leaves the box through the outlet port and conveyed to the condenser via a metal pipe. Fig. 1 and Plate 1 show the block diagram of experimental set up and schematic diagram of the experimental set up of steam injection respectively.

2.4 Experimental Set-up for Removal of NAPL from Unsaturated Zone Using Steam Injection with Magnetic Effect

The experiment was conducted in a galvanized steel box (Sand box) of dimension 110cmx74cmx8.5cm with a plain glass panel which will allow visual access of the sand packing in the sand box to observe the behaviors of contaminant (DNAPL). Steam was generated from steam boiler which operating on gas as its fuel and injected in to the sand box through the inlet port located at the middle edge of the sand box. The steam flow rate was adjusted using a flow control valve and monitored with flow meter and pressure gauges. Magnetic field was

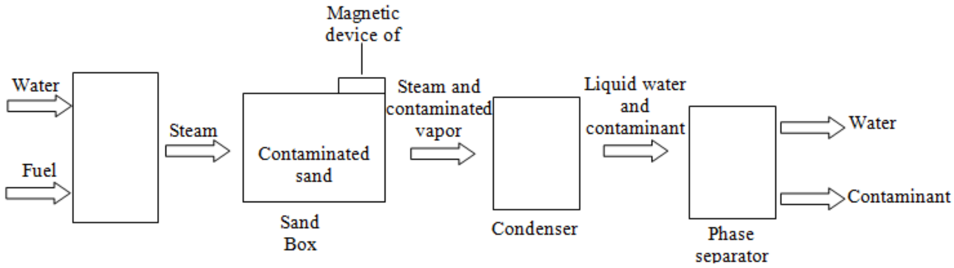

Fig. 1. Block Diagram of Experimental Set up of Steam Injection

Plate 1. Steam Boiler, Sand Box and Condenser Set-Up for the Experiment

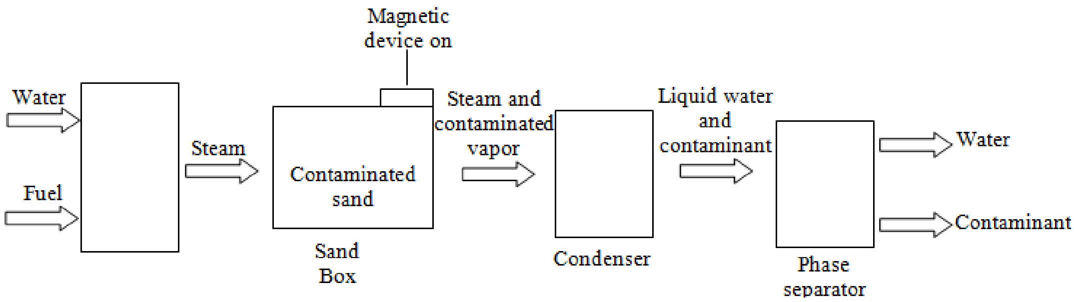

Fig. 2. Block Diagram of Experimental Set up of Steam Injection with Magnetic Effect

generated by electromagnetic inductor which induced magnetic field on to the metal rod perpendicularly positioned in the Sand box to the direction of flow of injecting steam. This electromagnetic device is capable of producing magnetic flux of varying values ranging from 1-3T [14]. Steam injected into the sand box and vapor of the contaminants leaves the box through the outlet port and conveyed to the condenser via a metal pipe.

2.5 Determination of Recovery Efficiency

Recovery efficiency was determined for each experiments performed on using steam injection only (0 T) and steam injection with magnetic field (1-3 T) for recovery of Carbon tetrachloride (contaminant) from the groundwater. The result from both methods was compared to each other to determine the most efficient method out of the two. And also, graph of cumulative volume of recovered contaminant (DNAPL) was plot against time for each of the experiments performed.

Recovery efficiency = Recovery volume of NAPL (Contaminant) / Initial volume of NAPL (contaminant)in sand box X 100 (9)

2.6 Comparative Study between Experimental Result of Steam Injection Only and Steam Injection with Magnetic Field

The experimental result of Effect of Magnetic Field on Removal of Non-aqueous Phase Liquid from Unsaturated Zone Using Steam Injection Only and Steam Injection with Magnetic Field was compared using descriptive and inferential statistics. The descriptive method used includes percentage while the inferential analysis used was correlation and Chi-square at 0.05 level of significant. The deviation of results was calculated with the equation 10.

$$\% \text{ Deviation} = \frac{Value\ of\ steam\ injection\ by\ author - value\ of\ steam\ injection}{value\ of\ steam\ injection\ only\ by\ an\ author} \times 100 \quad (10)$$

3. RESULTS AND DISCUSSION

3.1 Results of Soil Geophysical Test

The result of the soil geophysical test of the soil sample collected at in front of chemical engineering laboratory, Ladoke Akintola University of Technology, Ogbomoso, Oyo state to determine the Effects of Magnetic Field on Removal of Non Aqueous Phase Liquid from Unsaturated Zone using Steam Injection. The results of the soil moisture content, permeability, soil texture, porosity, soil grain size are as follows. Table 1 shows the result of soil moisture content of the soil used for the experiment.

Tables 2 and 3 show the summary of all result of soil properties test of soil sample used for the experimental investigation of effect of magnetic field on removal of non aqueous phase liquid from unsaturated zone using steam injection.

Table 1. Result of Soil Moisture Content Test

S/N	Description	1st Result	2nd Result
1	Container No (cup no)	243	345
2	Mass of cup (g)	29.40	30.70
3	Mass of dry soil (g)	15.60	42.70
4	Mass of cup + wet soil (g)	46.30	77.50
5	Mass of cup + dry soil (g)	45.00	73.40
6	Mass of water (g)	1.30	4.10
7	Water content (%)	8.33	9.60
	Average water content (%)	**9.0**	

Table 2. Result of Soil Permeability Test

S/N	Time (s)	Height (cm)
1	0.0	2.0
2	30.0	6.5
3	60.0	9.7
4	90.0	12.5
5	120.0	15.0
6	150.0	17.4
7	180.0	19.0
8	210.0	20.1
9	240.0	21.0
10	270.0	21.8
11	300.0	22.4
	K=0.001163779 cm/s	

Table 3. Properties of Soil Sample used for Experiment

S/N	Parameter	Value of the Result
1	Sand color	Light brown
2	Sample area (cm^3)	86.6250
3	Sample length (cm)	12.5000
4	Bulk Density (g/cm^3)	1.7600
5	Moisture content (%)	9.000
6	Dry density (g/cm^3)	1.6200
7	Specific Gravity	2.6000
8	Void ratio	0.0044
9	Porosity	0.42
10	Manometer Area	1.0000
11	Soil texture: sand, clay, silt (%)	64.5, 11.4, 24.1
12	Hydraulic constant (cm/s)	0.001163779

3.2 Removal of Dense Non Aqueous Phase Liquid (Carbon tetrachloride) from Unsaturated Zone using Steam Injection only

Table 4 show the cumulative recovered volume of contaminant (Carbon tetrachloride) after treating with steam injection only for another 30, 60, 90 and 120 minutes of remediation process were 25.6, 82.6, 155.4, and 160.6 mL respectively out of 200mL total initial volume of contaminant (Carbon tetrachloride) was recovered.

3.3 Effect of Magnetic Field on Removal of Dense Non Aqueous Phase Liquid (Carbon tetrachloride) from Unsaturated Zone using Steam Injection

The result of total cumulative volume and recovery efficiency of Light Non Aqueous Phase Liquid (Carbon tetrachloride) from unsaturated zone (sand box) after remediation of the contaminated soil with steam injection and combination of steam injection and magnetic field strength (1-3 T) at steam injection flow rate of 0.01 m^3/s for 120 minutes are as follows:

3.4 Removal of Dense Non Aqueous Phase Liquid (Carbon tetrachloride) from Unsaturated Zone using Steam Injection and Magnetic Field (1 T)

From Table 5, the recovered volumes were 61.2, 130.6, 177.8, and 178.45 mL when used steam injection with magnetic field strength (1 T) at 30, 60, 90,and 120 minutes. The recovery efficiency calculated for each of the recovered volumes were 30.60, 65.30, 88.90 and 89.45 %.

The calculated recovery efficiency for the same respective treatment time was 12.80, 41.30, 77.70 and 80.30% respectively. Within the first thirty minutes of commencement of the process, it was observed that the recovery rate was very small so as also the recovery efficiency too when comparing it with that of thirty to ninety minutes. This was because the injected steam losses its latent heat to raise the temperature of the sand box from room temperature to temperature enough to vaporize the water and the DNAPL and there was an increase in recovery volume of DNAPL (Carbon tetrachloride) between thirty minute to ninety minute of steaming which also increase the recovery efficiency, because the temperature of the sand box at this period was sufficient to vaporize the DNAPL (Carbon tetrachloride). But there was a reduction in recovery volume of DNAPL between ninety minute and one-twenty minute of the process. This might be as a result of reduction in the concentration of DNAPL (Carbon tetrachloride) in the sand box or some of the DNAPLs was lost through evaporation to the surrounding and was unable be recovered .

3.5 Removal of Dense Non Aqueous Phase Liquid (Carbon tetrachloride) from Unsaturated Zone using Steam Injection and Magnetic Field (2 T)

Table 6 shows the cumulative recovered volume of contaminant (Carbon tetrachloride) recovered when treated with steam injection with magnetic field (2 T) at 30, 60, 90 and 120 minutes were 70.8, 143.9, 189.1, and 189.9 mL respectively and the recovered efficiency for this treatment were 35.40, 71.95, 94.55 and 94.95 %.

3.6 Result of Removal of Dense Non Aqueous Phase Liquid (Carbon tetrachloride) from Unsaturated Zone using Steam Injection and Magnetic Field (3 T)

Table 7 shows the recovered volume and recovery efficiency, when treated the contaminated soil in the sand box with steam injection with magnetic field of 3 T to removed contaminant (Carbon tetrachloride) from the sand box for 30, 60, 90, and 120 minutes, the cumulative volume of Carbon tetrachloride recovered ware 70.6, 144.9, 189.7, and 190.7 mL respectively of the total Carbon tetrachloride content initially injected in to the soil in the sand box (200mL) and the recovery efficiency were 35.3, 72.45, 94.85, and 95.35 % respectively.

3.7 Comparing the Experimental Result of Removal of NAPL from Unsaturated Zone using Steam Injection Only and Steam Injection with Magnetic Fields

The method for data analysis was descriptive and inferential statistics. The inferential analysis used was Chi-square method to test the result of comparative study between experimental result of steam injection only and steam injection with magnetic fields on removal of non aqueous

Table 4. Recovered Volume/ Recovery efficiency of Removal of DNAPL (Carbon tetrachloride) from Sand Box using Steam Injection only

S/N	Time (minute)	Cumulative Recovered volume (mL)	Recovery Efficient (%)
1	0	0	0
2	30	39.4	19.70
3	60	99.7	49.85
4	90	163.5	81.75
5	120	164.1	82.05

Table 5. Recovered Volume/ Recovery efficiency of Removal of NAPL (Carbon tetrachloride) from Sand Box using Steam Injection and Magnetic Field Strength of 1 T

S/N	Time (minute)	Cumulative Recovered volume (mL)	Recovery Efficient (%)
1	0	0	0
2	30	61.2	30.60
3	60	130.6	65.30
4	90	177.8	88.90
5	120	178.9	89.45

Table 6. Recovered Volume/ Recovery efficiency of Removal of NAPL (Carbon tetrachloride) from Sand Box using Steam Injection and Magnetic Field Strength of 2 T

S/N	Time (minute)	Cumulative Recovered volume (mL)	Recovery Efficiency (%)
1	0	0	0
2	30	70.8	35.40
3	60	143.9	71.95
4	90	189.1	94.55
5	120	189.9	94.95

Table 7. Recovered Volume/ Recovery efficiency of Removal of NAPL (Carbon tetrachloride) from Sand Box using Steam Injection and Magnetic Field Strength of 3 T

S/N	Time (minute)	Cumulative Recovered volume (mL)	Recovery Efficiency (%)
1	0	0	0
2	30	70.6	35.3
3	60	144.9	72.45
4	90	181.7	94.85
5	120	190.7	95.35

phase liquids from unsaturated zone using steam injection. The recovery efficient steam injection with magnet (RESIM) on the remediation non aqueous phase liquid from unsaturated zone at different time of 30, 60, 90,and 120 minutes respectively for steam injection only and steam injection with magnetic field 1 T- 3 T) were evaluated: Fig. 3 and Table 8 show the Recovery Efficient of Steam Injection only and steam injection with Magnet field 1-3T on the removal of Dense Non Aqueous Phase Liquid from Unsaturated Zone at different time (30, 60, 90,and 120 minutes). From the figure, on treating the Carbon tetrachloride in the sand box with Steam Injection only, the recovery efficiency obtained for the steaming time of 120 minutes was 82.05 % which was similar with the work done by USEPA [7] with deviation of 3.47 %. While treating the contaminant (Carbon tetrachloride) for the same period with steam injection with magnetic field 1-3 T, the recovery efficiency was 89.45-95.35 %.

This shows that the more the steaming time and magnetic field the more the recovery efficiency of the remediation process at constant steam injection flow rate of $0.01m^3/s$. The surge in recovery efficiency of the remediation process was attributed to the decrease in amount of contaminant (Carbon tetrachloride) in the sand box after the remediation process. The soil type may influence the process of exit of Carbon tetrachloride considering the porosity of the soil which allows the persistence penetration of steam into the soil. This in-turn, will aid Carbon tetrachloride to vaporize and desorb from the soil particles. Sleep and McClure (2001), described volatile organic compounds as those compounds that vaporize at a temperature usually less than 100℃. The more the steam is injected into the soil in the sand box the more the Carbon tetrachloride vaporize from it because of its nature of volatility and this led to the reduction in Carbon tetrachloride and which eventually increases the recovery efficiency

of the remediation process. It was also observed that recovery efficiency of Carbon tetrachloride in the sand box when treated with steam injection with magnetic field 1-3T is higher than the one treated with steam injection only by 9.02-16.21%. This was because the magnetic field increases the rate of evaporation of NAPLs (Carbon tetrachloride) by reducing the strength of Van der Waals force which resulted to reduction in viscosity of Carbon tetrachloride, eventually increasing the recovery rate of NAPL (Carbon tetrachloride) in the sand box.

Tables 9 and 10 shows observed and expected recovered volume of carbon tetrachloride for steam injection with magnetic field 1-3 T and the calculated value of the result from the Tables showed observed and expected recovered volume of Carbon tetrachloride for steam injection with magnetic field 1-3 T. The calculated value of Chi-square (0.0557) was less than the critical value (16.92) at nine degree of freedom at 0.05 level of significance. This result implied that, there is a significant relationship between recovered volume of Carbon tetrachloride when treated with steam injection only and steam injection with magnetic field of 1-3 T [15,16].

Table 8. Observed Recovered Volume of Toluene for Steam Injection with Magnetic Field 1-3 T

Time (minute)	Volume Recovered at 0 T	Volume Recovered at 1 T	Volume Recovered at 2 T	Volume Recovered at 3 T	Total
0.0	0	0	0	0	0
30.0	25.6	25.7	29.6	30.2	111.1
60.0	57	62.2	65.3	67.4	251.9
90.0	72.8	76.3	74.7	74.1	297.9
120.0	5.2	3.2	2.1	1.5	12
Total	**160.6**	**167.4**	**171.7**	**173.2**	**672.9**

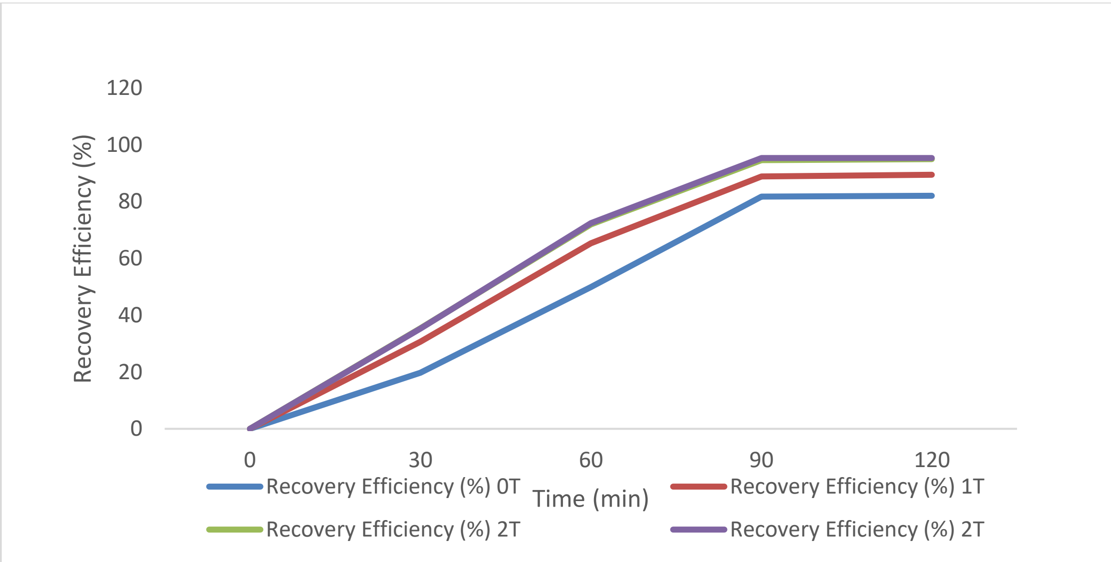

Fig. 3. Recovery Efficiency of NAPL (Carbon tetrachloride) from Sand Box using Steam Injection only and Steam Injection with Magnetic Field (1 -3 T)

Table 9. Observed Recovered Volume of Carbon tetrachloride for Steam Injection Only (0 T) and Steam Injection with Magnetic Field 1- 3 T

Time (minute)	Volume Recovered at 0 T	Volume Recovered at 1 T	Volume Recovered at 2 T	Volume Recovered at 3 T	Total	
0.0	0	0	0	0	0	
30.0	39.4	61.2	70.8	70.6	242	
60.0	60.3	69.4	73.1	74.3	277.1	
90.0	63.8	47.2	45.2	45.8	202	
120.0	0.6	1.1	0.8	0	2.5	
150.0	0	0	0	0		
Total		**164.1**	**178.9**	**189.9**	**190.7**	**723.6**

Table 10. Expected Recovered Volume of Carbon tetrachloride for Steam Injection Only (0 T) and Steam Injection with Magnetic Field 1- 3 T

Time (minute)	Volume Recovered at 0 T	Volume Recovered at 1 T	Volume Recovered at 2 T	Volume Recovered at 3 T	Total	
0.0	0	0	0	0	0	
30.0	54.8814262	59.8311222	63.5099502	63.7775014	242	
60.0	62.8415008	68.5091072	72.7215174	73.0278745	277.1	
90.0	45.8101161	49.9416805	53.0124378	53.2357656	202	
120.0	0.56695688	0.61809011	0.65609453	0.65885849	2.5	
150.0					0	
	Total	164.1	178.9	189.9	190.7	723.6
X^2 value						
P=	**0.05577048**		**Table value=**	**16.92**		

4. CONCLUSION

The study therefore, has been able to determine the effect of magnetic field on removal of Dense Non Aqueous Phase Liquid (DNAPL) from unsaturated zone using steam injection only and steam injection with magnetic field 1-3 T. And also to compare the remediation processes. The following conclusions were drawn from the research work:

1. The experimental result for the recovery efficiency of dense non aqueous phase liquid (Carbon tetrachloride) using steam injection only at 0.01m^3/s was 82.05%. Steam injection for remediation of porous media contaminated by DNAPL has been shown to be an efficient technology.
2. The experimental result for the recovery efficiency of light non aqueous phase liquid (Carbon tetrachloride) while steam injection of 0.01m^3/s and magnetic field 1-3 T yielded 89.45-95.35%. Better recovery efficiency of Carbon tetrachloride was obtained from Steam injection with magnetic field than steam injection only.
3. The recovery efficiency of DNAPL (Carbon tetrachloride) in the sand box treated with steam injection and magnetic field 1-3 T is higher than the one treated with steam injection only by 9.01-16.21% respectively.
4. This results shows that steam injection is efficient in the removal of LNAPL from unsaturated zone.. The addition of electromagnetic field pose a significant effect on the remediation processes since it increases the recovery efficiency and cut down the remediation process.

CONFERENCE DISCLAIMER

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DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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