American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-10, Issue-8, pp: 184-193
www.ajer.org
Research Paper Open Access

Experimental Investigation on Effect of Magnetic Field on Migration and Removal of Pollutant from Groundwater Using Steam Injection

A.A. Adegbola[1], M.A. Olojede[2], E.M. Olatunji[3], M. Adisa[3], D. Abiodun[3]
[123]*Department of Mechanical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Oyo State.*

ABSTRACT
Groundwater is of major importance to civilization, because it is the largest reserve of drinkable water in regions where humans can live. Although groundwater is less contaminated than surface waters, pollution of this major water supply has become an increasing concern with increasing industrialization. The aim of this research work is to carry out experimental investigation of magnetic effect on migration and removal of diesel from groundwater using steam injection.The steam was generated from the steam boiler and was supplied to the sand box at injection rate of 0.14m^3/s, pressure of 1.5bar and temperature of 150^{0}C. The initial volume of diesel used was 500ml. At the supply of the steam to the sand box, the mixture of underground water and diesel was heated and at temperature above their boiling points, the mixture change phase and vapourized from the chamber through the outlet or recovery side into the condenser and separated on cooling using phase separator.The experimental result for the recovery efficiency of diesel using steam injection only was obtained to be 66.04%. The experimental result for steam injection with magnetic effect at 1T and 2T were 70.20% and 73.60 respectively.Steam injection for remediation of porous media contaminated by NAPL has been shown to be an efficient remediation technology. The results showed that the pollutant spread area reduces with increasing magnetic strength. The study thus suggests that imposition of an external magnetic field may appreciably militate against pollutant migration in an aquifer and subsequently cut down on other remediation processes.

KEYWORDS: *Groundwater, Pollution, Magnetic effect, Steam Injection, Pollutant, Remediation*

Date of Submission: 04-08-2021 Date of acceptance: 17-08-2021

I. INTRODUCTION

Groundwater is the largest reserve of drinkable water in regions where humans can live. It is of major importance to civilization. The major drinking water sources include ground water, lakes and reservoirs, canals, atmospheric water generation, rain water harvesting, fog collection and sea water. Water is a major source for survival on this planet. Its conservation is therefore a priority. With the increase in demand, the supply needs to meet specific standards. Although groundwater is less contaminated than surface waters, pollution of this major water supply has become an increasing concern with increasing industrialization. The groundwater quality is endangered by numerous human activities. Often, water is contaminated with a mixture of contaminants. Drinking of contaminated water can be injurious to health.

A problem of major concern in industrialized regions is the contamination of the subsurface with organic NAPLs (Non Aqueous Phase Liquids). These contaminants are almost immiscible with water and will often be present as non-aqueous phase liquids (NAPL). Mercer and Cohen (1990) provide the following description of NAPL transport in subsurface. When spilled into the unsaturated zone the NAPL migrates downward due to gravity. The NAPL may spread horizontally due to capillary forces and heterogeneities and furthermore some of the NAPL may be immobilized as residual. If the spill is large enough the NAPL eventually reaches the saturated zone where it floats in the top of the capillary fringe if it is lighter than water (LNAPL) and migrates further downwards if it is denser than water (DNAPL).

Industrial activities during the last four to five decades have created a large number of sites where chemical spills have contaminated the subsurface. Contamination is basically found where chemicals have been used in large amounts and typically below old gas stations, dry cleaners, military bases, gas works etc. Typical contaminants are chlorinated solvents, gasoline/fuels, coal tar and creosote. The contamination of groundwater is posing a serious problem, since the contamination sources have not been controlled in an effective manner. These major sources are from industrial activities, agricultural practices and consumption actions.

Groundwater remediation will assist us in the eradication of some diseases which may arise as a result of contaminated water e.g. cholera, dysentery and hepatitis etc. Therefore, there is a need to get rid of these contaminants in order to save our environment from pollution and protect people's life from danger. Remediation is very important because the presence of contaminants in groundwater at concentrations above background levels demonstrates a high potential health and ecological risk. Some of the needs for remediation are stated as follows.

i. To separate pollutant from ground water.
ii. To prevent the migration of pollutant from ground water.
iii. To enhance recovery efficiency.

It is necessary to remediate a contaminated site because of the risk of human exposure to these chemicals combined with their toxicity. This is most often done by excavating the contaminated soil and treating it off site. However, at some sites the volume of contaminated soil might be too large or there might be buildings that make it impossible to excavate. Therefore remediation has to take place in situ without disturbing the soil. Traditional in situ remediation technologies are pump-and-treat in saturated zone and soil vapor extraction in the unsaturated zone. Unfortunately, these technologies have shown to be very inefficient at NAPL sites. The mass transfer rate from the heterogeneously distributed NAPL becomes diffusion-limited and large volumes need to be flushed to achieve clean-up. These sites have proved difficult to remediate and aggressive technologies are needed.

In recent years several in-situ remediation techniques have been developed. One of them is the thermally enhanced soil vapor extraction. It is concerned with an improved effectiveness of soil venting for the remediation of a NAPL contaminated unsaturated zone. (Davis, 1997; Davis, 1998) concluded that the main reason for the wide application of thermal treatment is that the mobility of the contaminant increases at elevated temperatures. The single most important removal mechanism is increased vapor pressure. Vapor pressure is a measure of volatility of a compound when it is present as a free phase liquid.

Remediation by steam injection is such a technology and it may be the optimal technology at heavily contaminated sites. Steam injection is found capable of providing a means to overcome these limitations and may in some case be able to achieve clean-up goals rapidly. With Steam injection, the contaminated water is heated and this strongly affects the physical-chemical properties of the contaminants in most cases to the benefit of the recovery process. Many researchers have found that the recovery from steam injection is related closely to heating rates

(EPA, 1995). However, this dependence is more related to steam properties and injection rates; the thermal properties of soils and the liquid contaminants have generally not been found to vary enough to affect the recovery achieved by steam injection (Hadim *et al*., 1993). Steam injection is the most commonly used thermal remediation technology. Steam injection was originally developed as an enhanced oil recovery technology where it was the reduction in viscosity that was most important (Warne *et al.*, 2002). Steam injection, also termed steam enhanced extraction, was initially developed by the petroleum industry for enhancing oil recovery, and has more recently been adapted to remediate soil and aquifers. Steam injection has been applied at some sites in the USA (USEPA, 2004). It has been applied in unsaturated as well as saturated zones (Smith and Hinchee, 1993) and is generally more efficient in porous media such as sand (Heron et al., 1998) than in low permeable soils (Balshaw-Biddle *et al*., 2000).The major equipment requirements for a steam injection system are the steam generator, the distribution system to the wells, the extraction system, and the coolers/condensers for the extracted fluids. Sale and McWhorther (2001) showed that near-complete removal of NAPL is necessary to reduce the short-term groundwater concentration.

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. Permanent magnets have been prepared from Ferromagnets of iron-based, nickel-based, cobalt-based or rare earth element-based compounds. Traditionally permanent magnets were considered weak intensity magnetic forces generating fields of less than 1 T however with the advancement in materials development and shape design parameters information; high intensity magnetic field strengths could be generated. In this regard multipole magnets find considerable advantages since it can generate fields greater than 2 T per unit length. The electromagnets generate maximum field of 2.4 T. The third category of magnetic separators is based on superconducting magnets which generate the highest intensity magnetic field. Superconducting magnets are capable of generating magnetic field from 2 to 10 T.

Magnetic separation is one purification technique that has been adapted from ore mining industries to anti-scale treatment of pipe lines to seeding magnetic flocculent. Magnetic separation offers a common technology adoption for purification of water which could be from oil removal to inorganic ion removal to organic contaminant removal to bacteria removal. To each technique whether adsorption, catalytic processes, membrane processes, it has been demonstrated that addition of magnetic component aides to improvisation in efficiency of separations. Reported observations of electromagnetic field effect on ground water remediation have proliferated with the improvement of available permanent magnets in groundwater remediation. Reservoir fluid have been shown to respond to magnetic field. Ivakhenko and Potter (2004) measured the magnetic susceptibility of various crude oils. Rani *et a.l*(2010) numerically investigated the effect of magnetic field in a porous medium. Similar efforts were carried out by Baoku *et. al*,(2010), Duwairi *et.al.*(2007) and Mansour *et. al*. (2010).While all the various remediation processes have given encouraging results, the need to reduce pollutant spread due to migration is equally of importance.

There are various available techniques for remediating contaminated sites as well as technologies presently under development. The feasibility of any remediation technology should be carefully evaluated from site to site based on site-specific information such as local geology and type of contamination. In some cases, a combination of treatment methods, used in a phased approach, is more efficient and effective than one method alone. The outcome of remedial treatments is determined by the fundamental physical, chemical and biological processes that control the distribution and fate of contaminants in the subsurface. A lot of problems had arisen from the situation of groundwater pollution. In order to provide solutions to these problems, then an effective way of remediating the contaminated water must be known and adopted. Many techniques known had been used to remediate groundwater pollution, however, the most efficient that will give a better and good removal result is been sourced for.

Some regions where this groundwater contamination is severe will appreciate works like this because it will help to provide insight to solving their challenge. Hence there is a need for the remediation techniques in order to reduce the spread of polluted migration and remove contaminant as much as possible. So there is a need to apply steam injection with magnetic effect as a remediation technique to enhance recovery efficiency. Such combination of steam injection and electromagnetic field effect is also regarded as treatment train, the combination of techniques in succession to enhance treatment efficiency (Tsitonaki, 2008).From the aforementioned studies, ground water remediation using steam injection with electromagnetic field effect is considerably more effective in removing LNAPL contamination from groundwater, reducing remediation time, preventing spread of contaminant and improving recovery efficiency. Such combination of steam injection with electromagnetic field effect is also known as treatment train. The use of combined technique in succession to enhance treatment performance, (Tsitonaki et al. 2008).

The aim of this research work is to perform experimental investigation in order to evaluate the effectiveness of ground water remediation using steam injection with magnetic effect.

II. MATERIALS AND METHODS

The experimental work was carried out in the fluid mechanics laboratory of mechanical engineering department of Ladoke Akintola University of Technology (LAUTECH), Ogbomoso and the work was divided into two parts which are stated as follows:

i. Groundwater remediation using steam injection only

ii. Groundwater remediation using steam injection with magnetic effect.

Experimental setup

The setup for the experiment consists of steam boiler and sandbox.

Steam boiler

This is the principal part of the set up as steam is generated. It consists of combustion chamber, furnace, blower, relief valve, pressure gauge, thermometer and the cylinder containing the water. The heat generated in the furnace which was gotten from the combustion of charcoal was then transferred to the water inside the cylinder to generate steam.

Sand Box

The sand box is a box of dimension 118 x 8.5 x 58cm as shown in fig. 1. It was made of steel to withstand high heat that was 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 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 sand box. The extraction port was at the right hand side of the chamber, used for collection of vaporized gas into the phase separator through the condenser. The main function of the condenser is to cool down the effluent gas. The cooling process was achieved by passing gas through a copper tube placed in a container containing ice. The phase separator was used to separate water from the condensed gases. The sand box was packed with a layer of dried coarse sand up to a level of 21cm. An amount of 6cm layer of stone was also packed to cover the surface of the sand. This prevents the mixing of sand with the water in the sand box.

Working process of steam injection

The steam boiler is a device used to generate steam, by applying heat energy derived from the combustion of charcoal in the furnace to water inside a cylinder placed above the furnace. The boiler incorporates the furnace in order to burn the charcoal and generates heat energy. This produces saturated steam at a rate which can vary according to the pressure above the boiling point of water. The higher the temperature of the furnace, the higher the rate of steam produced. The generated steam pass through the sandbox through a connecting or conducting pipe which then heat the polluted ground water then the pollutant passed out through the outlet which leads to the condenser. The phase separator was used to separate the diesel from water.

Experimental setup for steam injection and magnetic field effect

An electromagnetic field device was incorporated into the sandbox to create electromagnetic field to the test sample. It was incorporated to work simultaneously with steam injection and also the sandbox. The experimental setup was designed for both steam injection mechanism and magnetic purification and the system contains mainly of two major parts which are stated as follows:

- Steam boiler.
- Sand box.

Electromagnetic field device which was used to generate magnetic field, hence the magnetic field strength was varied to suit the expected purpose.

The contaminant

Light Non Aqueous Phase Liquid (LNAPL): Diesel i.e. liquid that are lighter than water which floats on water when mixed was used.

Groundwater remediation using steam injection

500ml of diesel was measured using a measuring cylinder which was taken as the initial volume of the contaminant and the measured contaminants was poured into the sand box which then contaminated the water in the sand box. Saturated steam from the steam boiler was then allowed to flow into the sand box through the injection port, the temperature of the contaminated water was then measured at different intervals as it is being heated up. When the boiling point of the contaminant is then reached, it started vaporizing the extraction port was then opened so as to collect effluent gases through the condenser into the phase separator. The recovered contaminant and little water i.e. the condensate was then allowed to settle in the phase separator some minutes in the phase separator for easy and efficient separation of water from the recovered contaminant. The final recovered volume of contaminant i.e. the main result of the experiment was then measured using the measuring cylinder so as to know the final volume of the contaminant recovered in the experiment. The whole process was then repeated so as to compare result. Below are the schematic diagrams of the experimental set up.

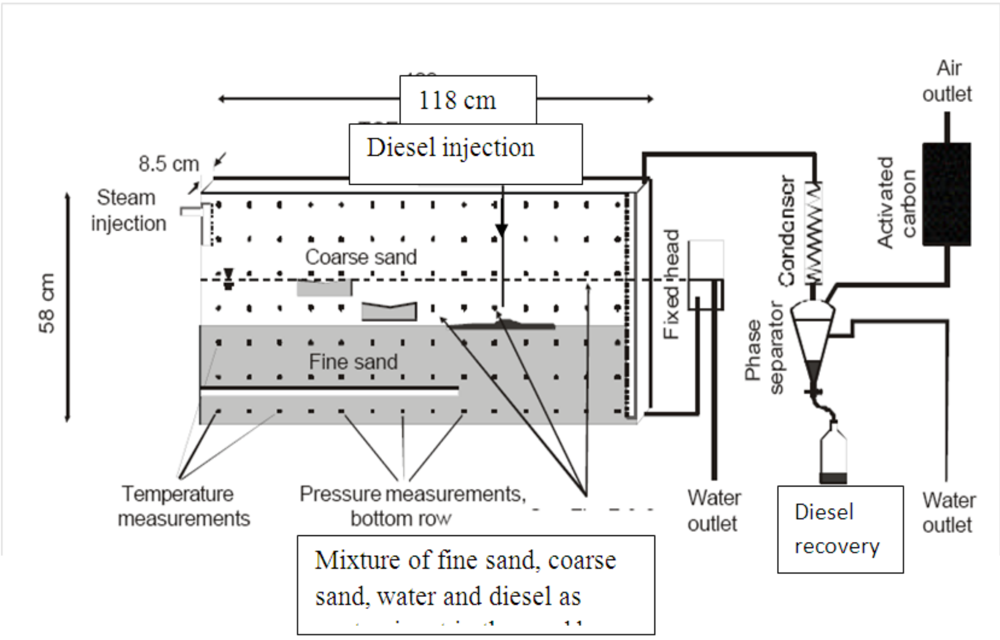

Fig. 1: Setup of groundwater remediation using steam injection Groundwater Remediation using Steam Injection With Magnetic effect

500ml of Diesel was measured using the measuring cylinder This is the initial volume of the contaminant. The measured contaminant was poured into the sand box and this contaminated the water in the sand box. The saturated steam from the steam boiler was then released into the sand box through the injection port.

The magnetic field device was then turned on which generated magnetic effect at field strength of 1T and 2T to the contaminated water in the sand box. As the contaminated water is being heated up, its temperature was measured at different interval. When the boiling point of the contaminant is then reached it began to vaporize. The extraction port was then opened to collect the effluent gases via the condenser in the phase separator. The condensate which contains the recovered contaminant and little water in the phase separator was then allowed to stay for some time which allowed easy separation of water from the recovered contaminant. The final recovered volume of contaminant was then measured using the measuring cylinder so as to know the final volume of contaminant for each experiment. The process was repeated to and the results were compared. Below is the schematic diagram of steam injection with electromagnetic effect:

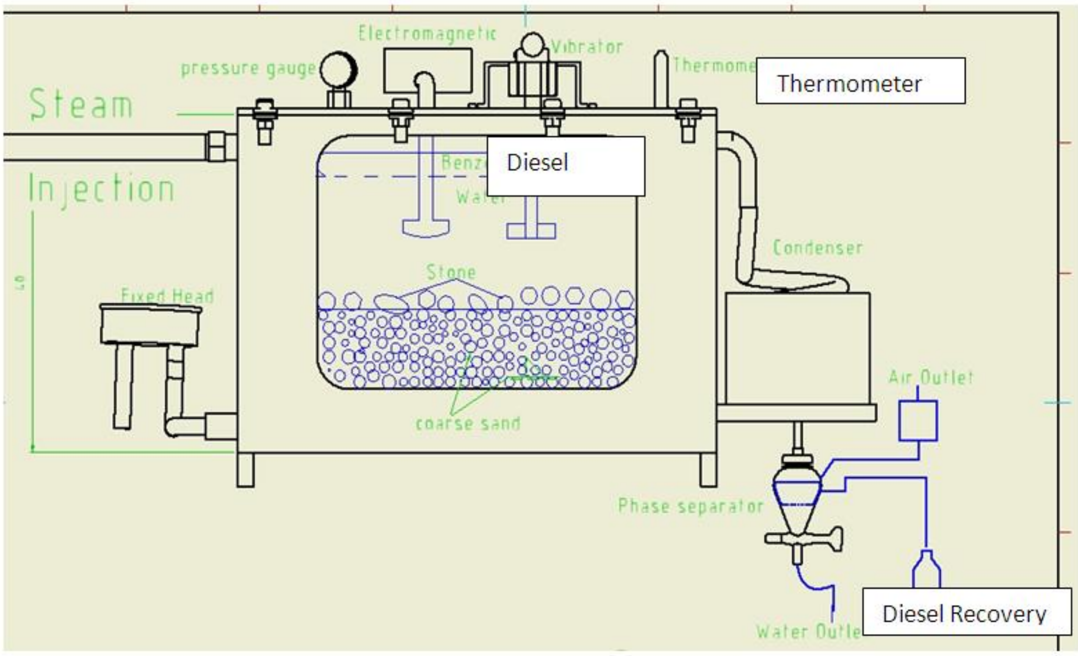

Fig. 2: Schematic diagram of groundwater remediation using steam injection with electromagnetic effect

Recovery efficiency calculation

Recovery efficiency= $\frac{V_2}{V_1} x\ 100\%$………………………………. (1)

V_1 =Initial volume of contaminant (ml)

V_2 = Final volume of contaminant recovered (ml)

III. RESULT AND DISCUSSION

When the experiment on effect of magnetic field on Groundwater remediation using Steam Injection was carried out, downward migration of separate phase contaminant to the groundwater zone was prevented for the investigated cases and the total amount of contaminant was recovered in the gas phase. The three mechanisms preventing downward migration can be identified from these experiments:

(i) Removal of pollutant with the non-condensable air.

(ii) More spatially distributed accumulation of pollutant due to less steep temperature gradients.

(iii) Lower velocity of evaporation front when compared to the velocity of heat front.

When injecting pure steam, boiling will occur and the removal will be limited by heat conduction and adventive flow out of the heterogeneities, which are faster mass transfer processes than diffusion (De Voe andUdell, 1998).

Experimental result for groundwater remediation process

Experimental results for the removal of diesel from groundwater using steam injection with the volume of the pollutant(diesel) measured as 500ml at the commencement of the experiment; steam injection rate of

0.14m^3/s, pressure of 1.5bar and temperature of 150^{0}C were reported in table 1.The results obtained from the remediation experiments of groundwater using steam injection with electromagnetic effect of 1Tesla and an initial volume of Diesel being 500ml. The recovery efficiency of each experiment with their corresponding time taken is shown in table 2.The results obtained from the remediation experiments of groundwater using steam injection with electromagnetic effect of 2Tesla at an initial volume of Diesel of 500ml. The recovery efficiency of each experiment with their corresponding time taken is shown in table 3.

Recovery efficiency of diesel from ground water using steam injection

Here, steam injection only was used in removing contaminant (diesel) from groundwater. Table 1 below shows the calculated values of recovery efficiency with respect to remediation time.

Table 1: Results of groundwater remediation using steam injection showing values of recovery efficiency determined from experimental results obtained

S/N	Time (hours)	Recovery Efficiency (%)
1	0	0
2	1	19.62
3	2	30.43
4	3	40.00
5	4	58.35
6	5	62.24
7	6	66.04

Graphical representation of steam injection with magnetic effect at 1T

Fig. 1 and 2 shows graph and chart for recovery efficiency of Diesel with time variation up to the actual completion of remediation process by using steam injection only. As the time increases diesel was recovered up to remediation time of 6hrs where 66.04% of diesel was finally recovered.

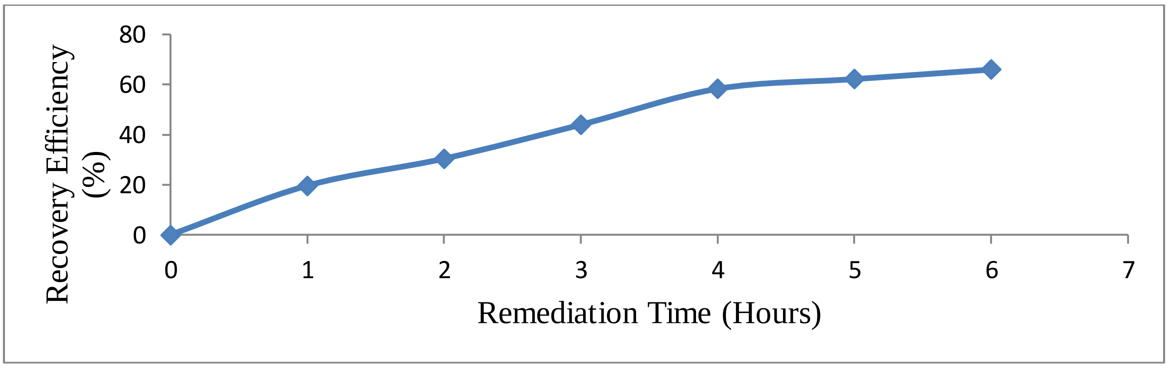

Fig. 1: Graph of recovery efficiency against time using steam injection only

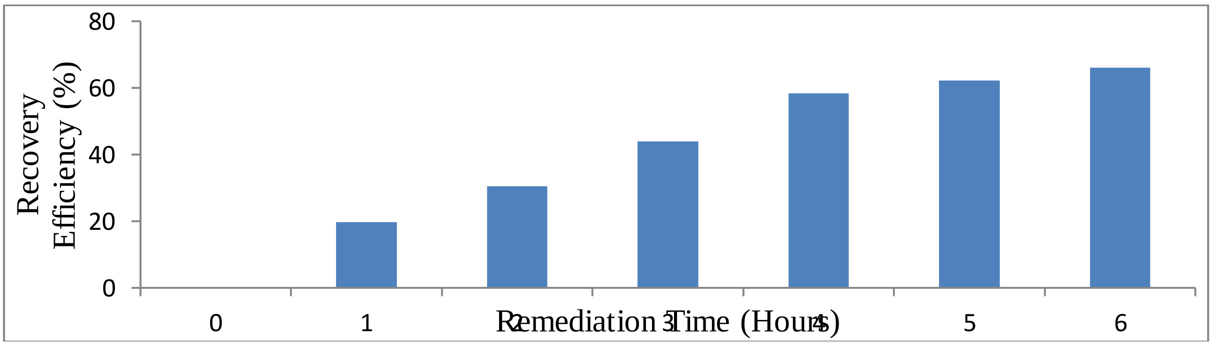

Fig. 2: Bar chart showing recovery efficiency against time using steam injection only

Recovery Efficiency of diesel from groundwater using Steam injection with Electromagnetic field effect at 1 Tesla

Steam injection was used simultaneously with magnetic field of 1T for removing the diesel from groundwater. Table 2 below gives the calculated values of recovery efficiency with respect to remediation time.

Table 2: Results of groundwater remediation using steam injection with electromagnetic effect of 1Tesla

S/N	Time (hours)	Recovery Efficiency (%)
1	0	0
2	1	20.94
3	2	33.85
4	3	48.14
5	4	60.00
6	5	65.35
7	6	70.20

Graphical representation of steam injection with magnetic effect at 1T

Fig. 3 and 4 shows graphical and chart for recovery efficiency of Diesel with time variation up to the actual completion of remediation process by using steam injection with magnetic field frequency 1T. As the time increases diesel was recovered up to remediation time of 6hrs where 70.20% of diesel was finally recovered.

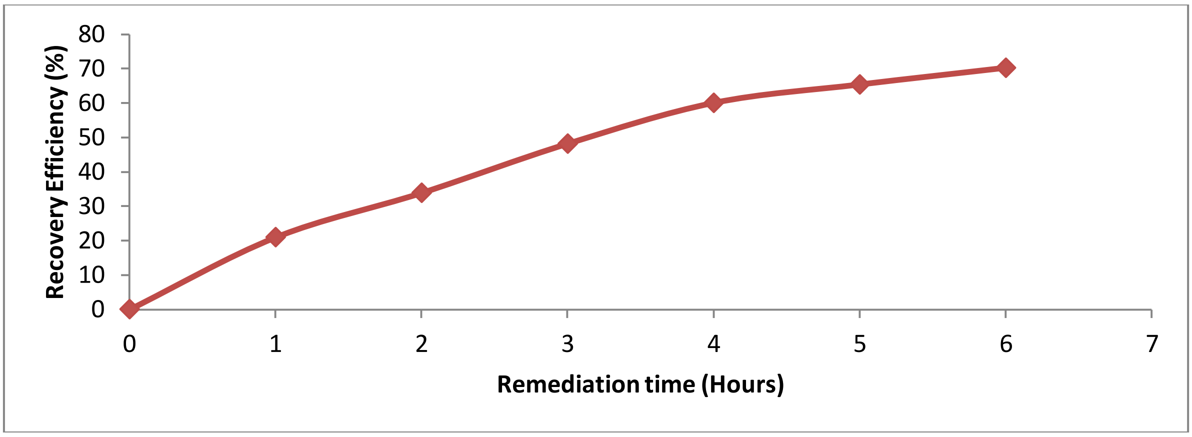

Fig. 3: Graph of recovery efficiency against time using steam injection with electromagnetic effect of 1Telsa

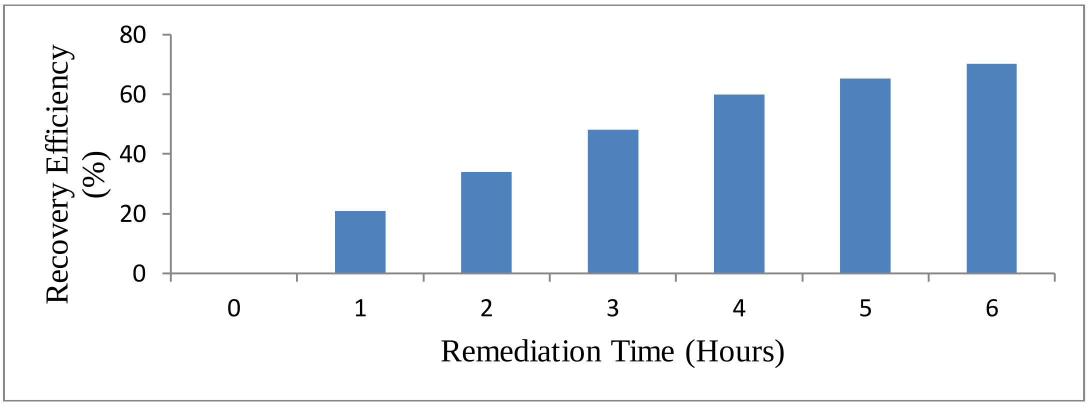

Fig. 4: Bar chart showing recovery efficiency against time using steam injection with electromagnetic effect of 1Telsa

Recovery Efficiency of diesel from groundwater using Steam injection with Electromagnetic field effect at 2 Tesla

Steam injection was used simultaneously with magnetic field of 2T for removing the diesel from groundwater. Table 3 below gives the calculated values of recovery efficiency with respect to remediation time.

Table 3: Results of groundwater remediation using steam injection with electromagnetic effect of 2Tesla

S/N	Time (hours)	Recovery Efficiency (%)
1	0	0
2	1	22.46
3	2	37.26
4	3	53.79
5	4	62.56

6	5	69.00
7	6	73.60

Fig. 5 and 6 shows graphical representation and bar chart for recovery efficiency of Diesel with time variation up to the actual completion of remediation process by using steam injection with magnetic field frequency 2T. As the time increases diesel was recovered up to remediation time of 6hrs where 73.60% of diesel was finally recovered.

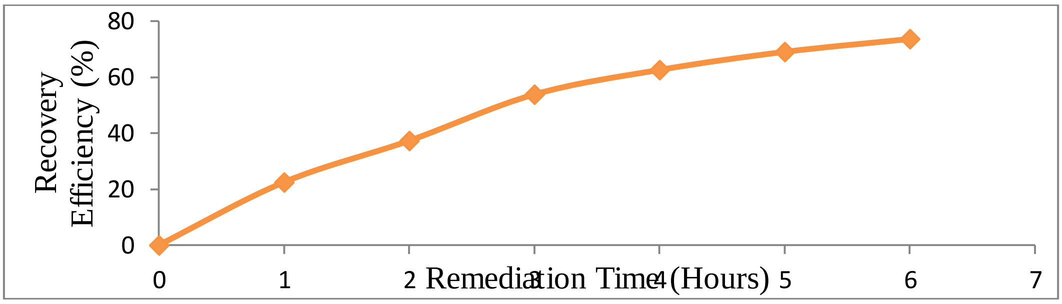

Fig. 5: Graph of recovery efficiency against time using steam injection with electromagnetic effect of 2Telsa

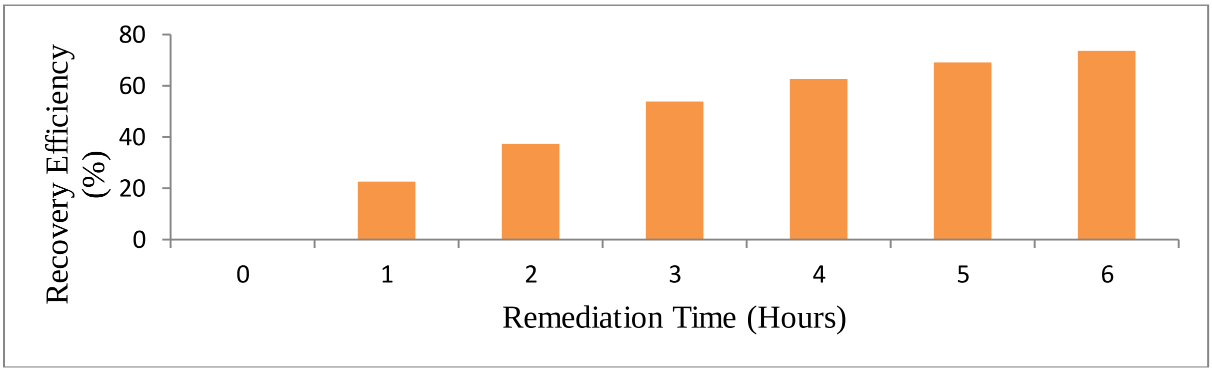

Fig. 6: Bar chart showing recovery efficiency against time using steam injection with electromagnetic effect of 2Telsa

Fig 7 and 8 shows the recovery efficiency of diesel with time variation up to the actual completion of remediation process by using steam injection and steam injection with electromagnetic field strength of 1Tand 2T. It shows that steam injection with electromagnetic field effects have higher recovery efficiencies than that of steam injection only.

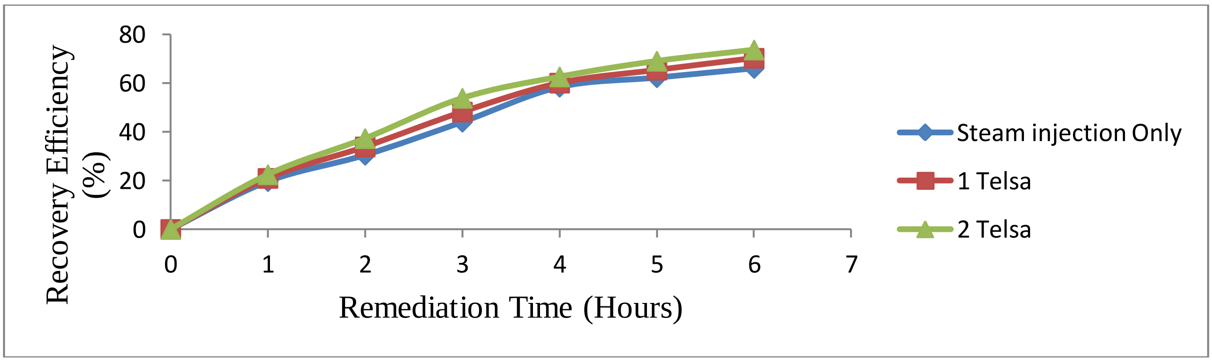

Fig. 7: Graph of recovery efficiency against time using steam injection with electromagnetic effect of 1 and 2 Telsa

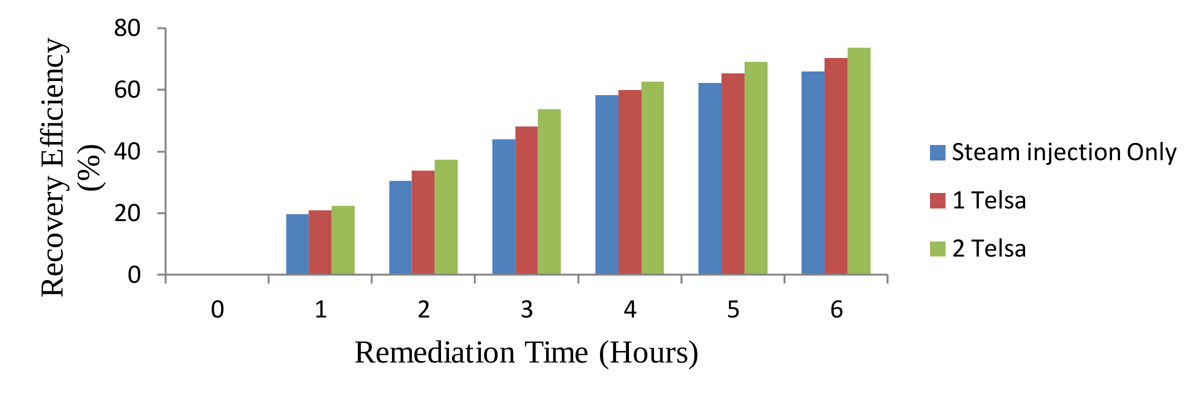

Fig. 8: Bar chart showing recovery efficiency against time using steam injection with electromagnetic effect of 1 and 2 Telsa

The results showed that for all the pollutants investigated, the pollutant spread area reduces with increasing magnetic strength. The study thus suggests that application of magnetic strength could be used as part of remediation plan for groundwater.

IV. CONCLUSION

In this research work, a modification of the steam injection technology is presented where the effect of steam injection with electromagnetic field effect were investigated. Steam and steam-magnetic experiments were performed in a two dimensional sand box to remediate unsaturated porous media contaminated by two different NAPLs. A bench scale laboratory experiment was carried out through incorporating steam injection and magnetic field. A test chamber of dimension 122x13.5x62cm was used to remediate diesel present as a separate phase from groundwater.

The experimental result for recovery efficiency of diesel using steam injection only was 66.04 % while the experimental result for that of steam injection with magnetic effect at 1T was 70.20% and that of 2T being 73.60%.This results shows that steam injection is efficient in the removal of NAPLs from contaminated ground water. 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. Ground water remediation using steam injection and magnetic effect is considerably more effective in the removal of NAPLs from groundwater. It reduces remediation time, prevent spreading of contaminant and improve recovery efficiency.

REFERENCES

[1]. Adegbola A. A., A.A. Dare (2018): Numerical investigation of groundwater remediation using steam injection with magnetic effect, *international journal of latest technology in engineering., Management and Applied sciences.* Volume VII (ix), pg 101 - 111

[2]. Balshaw-Biddle, K., Oubre, C.L. and Ward, C.H. (2000). *Steam and Electro-Heating for* Remediation of Tight Soils, Lewis Publishers, Boca Raton, FL, USA.

[3]. Davis, E. L (1997), How heat can enhance in-situ soil and aquifer remediation: Important chemical properties and guidance on choosing the appropriate technique, Robert S. Kerr Environmental Research Laboratory, *EPA*/540/S-97/502.

[4]. Davis, E. (1998). Steam Injection for Soil and Aquifer Remediation. Robert S. Kerr Environmental Research Laboratory. *EPA*/540/S-97/505.

[5]. De Voe, C. and Udell, K. S.,1998. Thermodynamic and Hydrodynamic Behavior of Water and DNAPLS During Heating. *Proceedings of First International Conference on Remediation of Chlorinated and Recalcitrant Compounds*, Monterey, USA, pp. 61-66. Battelle Press. Columbus, Ohio.

[6]. Environmental Protection Agency (1995), *In situ remediation technology status report*: Thermal enhancements, Office of Solid Waste and Emergency Response, Technology Innovation Office, *EPA*/542-K-94-009.

[7]. Hadim, A., F. H. Shah, and G. P. Korfiatis (1993), Laboratory studies of steam stripping of LNAPL*-contaminated soils, J. Soil Contamin.*, 2(1):37-5,.

[8]. Hunt, J. R., N. Sitar, and K. S. Udell,(1988) Non-aqueous phase liquid transport and cleanup Experimental studies, *Water Resour. Res.*, 24(8):1247-1269.

[9]. Heron, G., Van Zutphen, M.,Christensen, T.H. and Enfield, C.G. (1998). Soil Heating for Enhanced Remediation of Chlorinated Solvents. A Laboratory Study on Resistive Heating and Vapor Extraction in a Silty, Low-Permeable Soil Contaminated with Trichloroethylene, *Environ. Sci. Technol.*, 32 (10): 1474-1481.

[10]. EPA/540/R-94/510 (1995), Innovative Technology Evaluation Report, National Risk Management Research Laboratory, Cincinnati, OH.

[11]. Kronenbery K.J. (1985) ‘’ Experimental evidence for effect of magnetic fields on groundwater” *IEEE Transaction on Magnetive*. 21 (5): 2958-2061.

[12]. Mercer, J.W, Cohen, Skipp, D.C. and Giffin, D. (1990) Basics of Pump-and-Treat Ground Water Remediation Technology. *US Environmental Protection Agency report* EPA/600/8-90/003, Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma.

[13]. Myhill, M. A., and G. L. Stegemeier (1978), Steam-drive correlation and prediction, *J. Petrol. Technol.*, 173-182.

[14]. Sale, T. C. and McWhorter, D. B., (2001). Steady state mass transfer from singlecomponent dense nonaqueous phase liquids in uniform flow fields. *Water Resources Research*. 37: 393-404.

[15]. Singhal, A. K. (1980), Physical model study of inverted seven-spot steam floods in a pool containing conventional heavy oil, *J. Can. Petrol. Technol.*, 123-134.

[16]. Smith, L.A. and Hinchee, R.E. (1993). In Situ Thermal Technologies for Site Remediation, Ft. Lewis Publishers, *Boca Raton,* FL, USA.

[17]. Stewart, L. D., and K. S. Udell (1988), Mechanism of residual oil displacement by steam injection, *SPE Res. Eng.*, 1233-1242, November.

[18]. Stewart, L. D. and Udell, K. S. (1989). The Effects of Gravity and Multiphase Flow on the Stability of Steam Condensation Fronts in Porous Media, Multiphase Transport in Porous Media, *ASME HTD*.

[19]. Tsitonaki, A (2008) New technologies for water wastewater treatment. *A Survay of recent patents on chemical engineering*. 1:17-26.

[20]. Tognotti, L., M. Flytzani-Stephanopoulos, A. F. Sarofim, H. Kopsinis, and M. Stoukides (1991), Study of adsorption-desorption of contaminants on single soil particles using the electrodynamic thermogravimetric analyzer, *Environ. Sci. Technol.*, 25(1):104-109.

[21]. Udell, K.S. and Stewart, L.D. 1989. UCB-SEEHRL. 89-2. In: University of California, Berkeley, CA, USA.

[22]. Udell, K. S. 1997, University of California at Berkeley, Personal Communication.

[23]. U.S. Environmental Protection Agency. (2004), In Situ Thermal Treatment of Chlorinated Solvents Fundamentals and Field Applications, *EPA*542-R-04- 010 57.

[24]. Warne, G.A, Patel, r., Rauch , B., Ali., S., Moore, G., Mehta, R ., …. Zahacy, T. (2002) .17th World Petroleum congress Preview JCPT. *Journal of Canadian petroleum technology*, 41(08), 6-40.

[25]. WHO (1999) Regional office for Europe.

[26]. WHO (2014) Electromagnetic fields (EMF).

[27]. Yuan, Z. G (1990) Steam distillation of liquid hydrocarbon mixtures in porous media, Dissertation, Mechanical Engineering Department, University of California at Berkeley.

[28]. Yabloochinikov, B. A. (1999). Method of magnetic pulse welding an end fitting to a driveshaft tube of vehicular driveshaft: Google Patents.

APPENDICES

Plate 1.0: Steam boiler

Plate 2.0: Test chamber (Sand box) and condenser

Plate 3.0: Experimental setup