

Numerical Investigation of Groundwater Remediation using Steam Injection with Magnetic Effect

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Abstract: - Groundwater is of major importance to civilization, because it is the largest reserve of drinkable water in regions where humans can live. The pollution of groundwater by Non Aqueous Phase Liquid (NAPL) has become an increasing concern with industrialization. Although steam injection has been developed as one of the remediation techniques, the need for its improved recovery efficiency using other methods has been a subject of continuous study. The aim of this study was to investigate the effect of magnetic field on groundwater remediation using steam injection.

The governing equations for simulation of three phase flow in groundwater were developed based on conservation of mass, momentum and energy. The incorporated steam injection as a flux source and magnetic field as a body force. Numerical model was subsequently developed by solving the equations using finite element technique. The model was first used to determine recovery efficiency of benzene in an aquifer containing sand of porosity 0.2 and permeability of $1 \times 10^{-16} \text{ m}^2$ with steam injection at $0.01 \text{ m}^3/\text{s}$. Thereafter, recovery efficiency was determined for incidence of steam injection $0.01 \text{ m}^3/\text{s}$ with varying magnetic field 0.2–0.4 T in step of 0.1 T. The numerical model was used to determine the recovery efficiency of ethanol for all the cases treated in numerical investigations of recovery of benzene.

The numerical results for recovery efficiency of benzene using steam injection at $0.01 \text{ m}^3/\text{s}$ was 71.77% while that with magnetic field at 0.2–0.4 T yielded 79.28–87.28%. The numerical results for recovery efficiency of ethanol using steam injection at $0.01 \text{ m}^3/\text{s}$ was 74.75% while that with magnetic effect at 0.2–0.4 T yielded 80.61–86.22%.

A combined application of steam injection with magnetic field appreciably enhances groundwater remediation. The study thus suggests that application of magnetic strength could be used as part of remediation plan for groundwater.

Keywords: Non Aqueous Phase Liquid, Groundwater Remediation, Steam injection, Recovery efficiency, Magnetic field

I. INTRODUCTION

Water is an essential substance for living system and it is necessary for human survival on the earth (Tansel, 2008; Ambashta and Sillanpaa, 2010). As a result of the rising population over the last decades and significant rise in water consumption, it is very important to conserve not only the quantity of the underground water supply, but even more its quality. The main part of our drinking water is gained by the

extraction of groundwater out of aquifers in the subsurface. Groundwater is of major importance to civilization, because it is the largest reserve of drinkable water in regions where humans can live. About 40% of drinking water comes from the groundwater; almost 97% of the rural population drinks it and about 30–40% of the water used for agriculture comes from the groundwater (Sharma and Reddy, 2004). It is greater in quantity and more economical in distribution.

The pollution of this major supply has become an increasing concern with increasing industrialization due to numerous human activities. Groundwater quality is endangered by contaminations caused by industrial waste and accidents which release hazardous substances into the environment. These contaminants that are almost immiscible and insoluble in water will often be present as Non Aqueous Phase Liquids (NAPLs). Considerable efforts have been made to understand various phenomena associated with groundwater pollution. The remediation of Non Aqueous phase liquid (NAPL)-contaminated aquifers remains a significant challenge despite over two decades of active research and development. Innovative technologies for subsurface remediation, including in situ techniques based on heating the subsurface to enhance the recovery of organic contaminants, are increasingly being evaluated for use at specific sites as the limitations to the conventionally-used techniques are recognized (Davis, 1998).

Helmig et al. (1998) describe the comparison of one-dimensional steam injection experiments into sand-filled columns with numerical simulations. Based on that Class (1999) gives an example of the numerical simulation of a steam injection experiment into a column that was contaminated with xylene in residual saturation. White et. al (2004) modeled flow of nonvolatile NAPL and aqueous phases that account for mobile, entrapped, and residual NAPL in variably saturated water-wet porous media and compared against results from detailed laboratory experiments. A two-dimensional intermediate scale sand box experiment was performed by Gudjerg et al. (2004) where an organic contaminant was emplaced below the water table at the interface between a coarse and a fine sand layer. Steam was injected above the water table and after an initial heating period the contaminant was recovered at the outlet. The experiment was successfully modeled using the numerical

code T2VOC and the dominant removal mechanism was identified to be heat conduction induced boiling of the separate phase contaminant. Yang et. al (2003) carried out numerical modeling for groundwater remediation in Dublin, Ireland. The model was used to characterize contaminants at three dimensional scale.

Reservoir fluids have been shown to respond to magnetic field. Ivakhenko and Potter (2004) measured the magnetic susceptibility of various crude oils. Rani et al (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). Magnetism is a unique physical property that independently helps in water purification by influencing the physical properties of contaminants in water. 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. Dare and Sasaki (2012) carried out numerical investigation of magnetic effect on pollutant migration in groundwater. The study thus suggests that application of magnetic strength could be used as part of remediation plan for groundwater.

While all the various remediation processes have given encouraging results, the need to improve recovery efficiency is equally of importance. This work has thus investigated numerically the effect of magnetic field on groundwater remediation using steam injection.

II. BASIC GOVERNING EQUATIONS

The basic equations for modeling groundwater pollutants movement as given by Class et. al (2002) and incorporating magnetic terms are presented below

The mass balances for each component

$$\frac{\partial (\rho_{w mol} X_w^k S_w + \rho_{g mol} X_g^k S_g + \rho_{n mol} X_n^k S_n)}{\partial t} - \text{div} \left\{ \frac{k_{rw}}{\mu_w + \sigma_w B^2} \rho_{w mol} X_w^k \mathbf{K} (\text{grad } p - \rho_{w mass} \mathbf{g}) \right\} - \text{div} \left\{ \frac{k_{rg}}{\mu_g + \sigma_g B^2} \rho_{g mol} X_g^k \mathbf{K} (\text{grad } p - \rho_{g mass} \mathbf{g}) \right\} - \text{div} \left\{ \frac{k_{rn}}{\mu_n + \sigma_n B^2} \rho_{n mol} X_n^k \mathbf{K} (\text{grad } p - \rho_{n mass} \mathbf{g}) \right\} + D_{pm}^k \mathbf{K} \rho_{g mol} (\text{grad } X_g^k) - q^k = 0 \quad (1)$$

With the supplementary constraints

$$S_w + S_g + S_n = 1 \quad (2)$$

$$p_n = p_g - \vartheta p_{cgm} S_g - (1 - \vartheta) [p_{cgw} S_w - p_{cnw} (S_w = 1)] \quad (3)$$

$$p_w = p_n - \vartheta p_{cnw} S_w - (1 - \vartheta) [p_{cnw} (S_w = 1)] \quad (4)$$

$$\frac{\partial (\rho_{w mass} U_w S_w + \rho_{g mass} U_g S_g + \rho_{n mass} U_n S_n)}{\partial t} + \frac{\partial (1 - \phi) \rho_R C_R T}{\partial t} - \text{div} \lambda_{pm} \text{grad } T - \text{div} \left\{ \frac{k_{rw}}{\mu_w} \rho_{w mass} h_w K (\text{grad } P_w - \rho_{w mass} \mathbf{g}) \right\} - \text{div} \left\{ \frac{k_{rg}}{\mu_g} \rho_{g mass} h_g K (\text{grad } P_g - \rho_{g mass} \mathbf{g}) \right\} - \text{div} \left\{ \frac{k_{rn}}{\mu_n} \rho_{n mass} h_n K (\text{grad } P_n - \rho_{n mass} \mathbf{g}) \right\} + \text{div} \{ D_{pm}^w \rho_{g mol} h_g^w M_{wt}^w \text{grad } X_g^g \} + \text{div} \{ D_{pm}^a \rho_{g mol} h_g^a M_{wt}^a \text{grad } X_g^a \} + \text{div} \{ D_{pm}^c \rho_{g mol} h_g^c M_{wt}^c \text{grad } X_g^c \} - q^h \quad (5)$$

where μ = dynamic viscosity, ρ = fluid density, S =saturation, ϕ = porosity

k_w =relative permeability, σ = electric conductivity of the medium, k = fluid phase, p = fluid pressure, X = mole fraction, n =contaminant, w = water , g = gas, B = magnetic flux and σ =electrical conductivity of the medium, h_α =the specific enthalpy of phase α and is given as the sum of the specific internal energy u_α and the volume changing work p_α / r_α mass . ρ_R = density of the soil grains, C_R = specific heat capacity of the porous matrix and λ_{pm} = Overall heat conductivity of the fluid filled porous medium.

Equations (3) and (4) determine the liquid phase pressures p_n and p_w from the gas phase pressure p_g by assuming that phase interfaces exist only between water and NAPL and between NAPL and gas.

III. DETERMINATION OF FLUID PROPERTIES FOR THE NUMERICAL SIMULATION

There are certain fluid properties in the derived governing equations Eqn (1-5) that needed to be determined before the simulation can be successfully carried out. These properties are density, viscosity, vapour pressures, thermal conductivity, diffusion and enthalpy. The various relationships for these properties are hereby presented.

The law of corresponding states

The two-parameter corresponding state theory asserts that if pressure, volume and temperature are divided by the corresponding critical properties, the function relating reduced pressure to reduced volume and reduced temperature becomes the same for all substances.

$$P_r = P/P_C \quad (6)$$

$$V_r = V/V_C \quad (7)$$

$$T_r = T/T_C \quad (8)$$

Saturated liquid Densities as a Function of Temperature

Racket (1970) proposed that saturated liquid volumes be calculated by

$$V_s = V_c Z_c^{(1-T/T_c)^{2/7}} \quad (9)$$

$$V_s = \frac{RT_c}{P_c} Z_c^{1+(1-T/T_c)^{2/7}} \quad (10)$$

Where V_s = saturated liquid volume, V_c = critical volume, Z_c = critical compressibility factor, T_c = critical temperature and R.

Yamada and Gunn (1973) proposed that Z_c in Eq. (10) be correlated with the acentric factor:

$$V_s = V_c (0.29056 - 0.08775w)^{(1-T/T_c)^{2/7}} \quad (11)$$

Densities of Liquid Mixtures at their Bubble Point

In order to extend equations of Eq. (11) to mixtures, mixing rules are required. Li (1971) and Spencer and Danner (1973) recommended

$$V_m = R \left(\sum_i \frac{x_i T_{ci}}{P_{ci}} \right) Z_{RAM}^{[1+(1-T_r)0.2857]} \quad (12)$$

$$Z_{RAM} = \sum x_i Z_{RAI} \quad (13)$$

With the relation of Yamada and Gunn (1973)

$$Z_{RAI} = 0.29056 - 0.08775w_i \quad (14)$$

Where $T_r = T/T_{cm}$.

Spencer and Danner (1973) recommend the mixing rules of Chueh and Prausnitz (1976).

$$T_{cm} = \sum_i \sum_j \varphi_i \varphi_j T_{cij} \quad (15)$$

$$\varphi_i = \frac{x_i V_{ci}}{\sum_j x_j V_{cj}} \quad (16)$$

$$1 - k_{ij} = \frac{8(V_{ci} V_{cj})^{1/2}}{(V_{ci}^{1/3} + V_{cj}^{1/3})^3} \quad (17)$$

$$T_{cij} = (1 - k_{ij})(T_{ci} T_{cj})^{1/2} \quad (18)$$

Li's method sets $k_{ij} = 0$ for Eq.(19). The HBT method of Eq. (15) to (18) has been extended to mixtures by Hankinson and Thomson (1979) with

$$T_{cm} = \frac{[\sum_i x_i (V_{ci} T_{ci})^{1/2}]^2}{V_{cm}} \quad (19)$$

$$V_{cm} = 0.25[\sum_i x_i V_i^* + 3(\sum_i x_i V_i^{*2/3})(\sum_i x_i V_i^{*1/3})] \quad (20)$$

$$w_m = \sum_i^n x_i w_{srki} \quad (21)$$

$$V_m = V^* V^{(0)} (1 - w_m V^{(\delta)}) \quad (22)$$

Correlation and Extrapolation of Vapour-Pressure Data

When the vapor phase of a pure fluid is in equilibrium with its liquid phase, the quality of chemical potential, temperature, and pressure in both phases leads to the Clapeyron equation (Smith, et al., 1996).

$$\ln P_{vp} = A \quad (23)$$

Boublik (1984) presents tabulations of experimental data that have been judged to be of high quality for approximately 1000 substances. Antoine in 1888 proposed a simple modification of Eq. (23) which has been widely used over limited temperature ranges.

$$\log_{10} P_{vp} = A - \frac{B}{T+C-273.15} \quad (24)$$

Where T is in kelvins, Values of A, B and C are tabulated for a number of materials in Appendix A with P_{vp} in bars and T in K. Additional tabulations of Antoine constants may be found in Boublik, et al. (1984), Dean (1999) and Yaws (1992).

Enthalpy of Vaporization at the Normal Boiling

A pure-component constant that is occasionally used in property correlations is the enthalpy of vaporization at the normal boiling point ΔH_{vb} . Vetere (1995) proposed an expression to correlate vapor pressures so that acentric factor is eliminated. When applied to the normal boiling point:

$$\Delta H_{vb} = RT_b \frac{(1-T_{br})^{0.38} (\ln P_c - 0.513 + 0.5066 / (P_c T_{br}^2))}{1-T_{br} + F(1-(1-T_{br})^{0.38}) \ln T_{br}} \quad (25)$$

F is 1.05 for C_2+ alcohols and dimerizing compounds such as SO_3 , NO and NO_2 . For all other compounds investigated by Vetere, F is 1.0. When T_c and P_c are not available, Vetere proposed

$$\Delta H_{vb} = RT_b = (A + B \ln T_b + \frac{CT_b^{1.72}}{M'}) \quad (26)$$

M' is a fictitious molecular weight that is equal to the true molecular weight for most compounds.

Estimation of Low-Pressure Gas Viscosity

Experimental values of low-pressure gas viscosities are compiled in Landolt-Bornstein (1955), Stephan and Lucas (1979), and Vargaftif, et al. (1996). Literature references for a number of substances along with equations with which to calculate gas viscosities based on critically evaluated data may be found in Daubert, et al. (1997). Gas phase viscosity information can also be found in Dean (1999), Lide (1999), Perry and Green (1997), and Yaws (1995).

The first-order Chapman-Enskog viscosity equation was given as

$$\eta = \frac{(26.69)(MT)^{1/2}}{\sigma^2 \Omega_v} \quad (27)$$

In order to use this relation to estimate viscosities, the collision diameter σ and the collision integral Ω_v must be found. For any potential curve, the dimensionless temperature T^* is related to ε by

$$T^* = \frac{kT}{\varepsilon} \quad (28)$$

Where k is Boltzmann's constant and ε is the minimum of the pair-potential energy.

Neufeld, et al. (1972) proposed an empirical equation which is convenient for computer application:

$$\Omega_v = [A(T^*)^{-B}] + C[\exp(-DT^*)] + E[\exp(-FT^*)] \quad (29)$$

Where $T^* = kT/\varepsilon$, $A = 1.16145$, $B = 0.14874$, $C = 0.52487$, $D = 0.77320$, $E = 2.16178$ and $F = 2.43787$. Equation (29) is applicable from $0.3 \leq T^* \leq 100$ with an average deviation of only 0.064%.

Chung, et al. (1984, 1988) have employed Eq. (29) with

$$\frac{\varepsilon}{k} = \frac{T_c}{1.2593} \quad (30)$$

$$\sigma = 0.809V_c^{1/3} \quad (31)$$

Where ε/k and T_c are in kelvins, σ is in angstroms and V_c is in cm^3/mol .

$$T^* = 1.2595T_r \quad (32)$$

Their final result can be expressed as:

$$\eta = 40.785 \frac{F_c(MT)^{1/2}}{V_c^{2/3}\Omega_v} \quad (33)$$

Where η = viscosity, μ M = molecular weight, g/mol T = temperature, K V_c = critical volume, cm^3/mol Ω_v = viscosity collision integral from Eq. (33) and $T^* = 1.2593T_r$

$$F_c = 1 - 0.275\omega + 0.059035\mu_r^4 + \kappa \quad (34)$$

Where ω is the acentric factor and κ is a special correction for highly polar substances such as alcohols and acids. When V_c is in cm^3/mole , T_c is in kelvins and μ is in debyes,

$$\mu_r = 131.3 \frac{\mu}{(V_c T_c)^{1/2}} \quad (35)$$

Viscosities of Gas Mixtures at Low Pressures

The rigorous kinetic theory of Chapman and Enskog can be extended to determine the viscosity of low-pressure multicomponent mixtures (Brokaw, 1968; Hirschfelder, et al., 1954; Kestin, et al., 1976). In a further simplification of the kinetic theory approach, Wilke (1950) neglected second-order effects and proposed:

$$\eta_m = \sum_{i=1}^n \frac{y_i \eta_i}{\sum_{j=1}^n y_j \varphi_{ij}} \quad (36)$$

Where

$$\varphi_{ij} = \frac{[1 + (\eta_i/\eta_j)^{1/2} (M_j/M_i)^{1/4}]^2}{[8(1 + M_i/M_j)]^{1/2}} \quad (37)$$

φ_{ij} is found by interchanging subscripts or by

$$\varphi_{ji} = \frac{\eta_j M_i}{\eta_i M_j} \varphi_{ij} \quad (38)$$

For a binary system of 1 and 2, with Eqs. (37) to (38),

$$\eta_m = \frac{y_{1\eta_1}}{y_1 + y_2 \varphi_{12}} + \frac{y_{2\eta_2}}{y_2 + y_1 \varphi_{21}} \quad (39)$$

Where η_m = viscosity of the mixture, η_i, η_2 = pure component viscosities

y_1, y_2 = mole fractions

and

$$\varphi_{ij} = [1 + (\eta_i/\eta_j)^{1/2} (M_j/M_i)^{1/4}]^2 \quad (40)$$

$$\varphi_{21} = \varphi_{12} \frac{[1 + (\eta_1/\eta_2)^{1/2} (M_2/M_1)^{1/4}]^2}{[8(1 + (M_1/M_2))]^{1/2}} \quad (41)$$

$$\varphi_{21} = \varphi_{12} \frac{\eta_2 M_1}{\eta_1 M_2} \quad (42)$$

As an approximate expression for φ_{ij} of Eq. (42), the following is proposed (Herning and Zipperer, 1936)

$$\varphi_{ij} = \left(\frac{M_j}{M_i}\right)^{1/2} = \varphi_{ji}^{-1} \quad (43)$$

Estimation of Low-Temperature Liquid Viscosity

Orrick and Erbar (1974) employs a group contribution technique to estimate A and B in Eq. (44).

$$\ln \frac{\eta_L}{\rho_L^M} = A + \frac{B}{T} \quad (44)$$

where η_L = liquid viscosity, cP ρ_L = liquid density at 20°C, g/cm^3

M = molecular weight, T = temperature, K

Prezdziecki and Sridhar (1985) Method

In this technique, the authors propose using the Hildebrand-modified Batschinski equation (Batschinski, 1913; Hildebrand, 1971; Vogel and Weiss, 1981)

$$\eta_L = \frac{V_o}{E(V - V_o)} \quad (45)$$

Where η_L = liquid viscosity, cP V = liquid molar volume, cm^3/mol

And the parameters E and V_o are defined below.

$$E = -1.12 + \frac{V_c}{12.94 + 0.10M - 0.23P_c + 0.024T_{fp} - 11.58(T_{fp}/T_c)} \quad (46)$$

$$V_o = 0.0085wT_c - 2.02 + \frac{V_m}{0.342(T_{fp}/T_c) + 0.894} \quad (47)$$

Where T_c = critical temperature, K P_c = critical pressure, bar V_c = critical volume, cm^3/mol

M = molecular weight, g/mol, T_{fp} = freezing point, K ω = acentric factor V_m = liquid molar volume at T_{fp} , cm^3/mol

The authors recommend that V_m and V be estimated from T_{fp} and T by the Gunn-Yamada (1971) method. In this method, one accurate value of V is required in the temperature range of applicability of Eq. (47). The datum point is defined as V^R at T^R , then at any other temperature T,

$$V(T) = \frac{f(T)}{f(T^R)} V^R \quad (48)$$

Where

$$f(T) = H_1(1 - \omega H_2) \quad (49)$$

$$H_1 = 0.33593 - 0.33953T_r + 1.51941T_r^2 - 2.02512T_r^3 + 1.11422T_r^4 \quad (50)$$

$$H_2 = 0.29607 - 0.09045T_r - 0.04842T_r^2 \quad (51)$$

Liquid Mixture Viscosity

Based on a corresponding-states treatment for mixture compressibility factors (Teja, 1980; Teja and Sandler, 1980), Teja and Rice proposed an analogous form for liquid mixture viscosity.

$$\ln(\eta_m \varepsilon_m) = \ln(\eta \varepsilon)^{(R1)} + [\ln(\eta \varepsilon)^{(R2)} - \ln(\eta \varepsilon)^{(R1)}] \frac{\omega_m - \omega^{(R1)}}{\omega^{(R2)} - \omega^{(R1)}} \quad (52)$$

Where the superscript (R1) and (R2) refer to two reference fluids. η is the viscosity, ω the acentric factor, and ε is a parameter defined here as :

$$\varepsilon = \frac{V_c^{2/3}}{(T_c M)^{1/2}} \quad (53)$$

The rules suggested by the authors to compute these mixture parameters are:

$$V_{cm} = \sum_i \sum_j x_i x_j V_{cij} \quad (54)$$

$$T_{cm} = \frac{\sum_i \sum_j x_i x_j V_{cij}}{V_{cm}} \quad (55)$$

$$M_m = \sum_i x_i M_i \quad (56)$$

$$w_m = \sum_i x_i w_i \quad (57)$$

$$V_{cij} = \frac{(V_{ci}^{1/3} + V_{cj}^{1/3})}{8} \quad (58)$$

$$T_{cij} V_{cij} = \Psi_{ij} (T_{ci} T_{cj} V_{ci} V_{cj})^{1/2} \quad (59)$$

Ψ_{ij} is an interaction parameter of order unity which must be found from experimental data.

Thermal Conductivity

Through rather elementary arguments, the thermal conductivity of an ideal gas was found to be equal to $vLC_v n/3$, where v is the average molecule velocity, L is the mean free path, C_v is the constant volume heat capacity per molecule, and n is the number densities of molecules. It is quite inaccurate. For monatomic gases, which have no rotational or vibrational degrees of freedom, a more rigorous analysis yields

$$\lambda = \frac{25}{32} (\pi m k T)^{1/2} \frac{C_v/m}{\pi \sigma^2 \Omega_v} \quad (60)$$

or, written for computational ease, with $C_v = \frac{3}{2} k$,

$$\lambda = 2.63 \times 10^{-23} \frac{(T/M)^{1/2}}{\sigma^2 \Omega_v} \quad (61)$$

Where λ = thermal conductivity, W/(m.k) T = temperature, K k = Boltzmann's constant = 1.3805×10^{-23} J/k M = molecular weight, kg/mo σ = characteristic dimension of molecule, m

Ω_v = collision integral dimensionless

Thermal Conductivities of Polyatomic Gases

The reduced thermal conductivity may be expressed as

$$\lambda_r = \lambda \Gamma \quad (62)$$

$$\Gamma = \left[\frac{T_c (M')^3 N_o^2}{R^5 P_c^4} \right]^{1/6} \quad (63)$$

In SI units, if $R = 8314$ J/(kmol K), N_o (Avogadro's number) = 6.023×10^{26} (kmol)⁻¹, and with T_c in kelvins, M' in kg/mol, and P_c in N/m², Γ has the units of m.K/W or inverse thermal conductivity. In more convenient units,

$$\Gamma = 210 \left(\frac{T_c M^3}{P_c^4} \right) \quad (64)$$

Where Γ is the reduced, inverse thermal conductivity, T_c is in kelvins, M is in g/mol, and P_c is in bars.

The reduced thermal conductivity was employed by Roy and Thodos (1970), who, however, separated the $\lambda_r = \lambda \Gamma = (\lambda \Gamma)_{tr} + (\lambda \Gamma)_{int}$

Where λ = low-pressure gas thermal conductivity, W/(m.K) and Γ is defined in Eq. (65).

$$(\lambda \Gamma)_{tr} = 8.757 [\exp(0.0464T_r) - \exp(-0.2412T_r)] \quad (65)$$

$$(\lambda \Gamma)_{int} = C f(T_r) \quad (66)$$

Chung, et al. developed an approach similar to that of Mason and Monchick (1962) to obtain a relation for λ . By using their form and a similar one for low-pressure viscosity [Eq. (67)], one obtains

$$\frac{\lambda M'}{\eta C_v} = \frac{3.75 \Psi}{C_v/R} \quad (67)$$

Where λ = thermal conductivity/(m.K) M' = molecular weight, kg/mol

η = low-pressure gas viscosity, N.s/m² C_v = heat capacity at constant volume, J/(mol.K)

R = gas constant, 8.314 J/(mol.K)

$$\Psi = 1 + \alpha \{ [0.215 + 0.28288\alpha - 1.061\beta + 0.26665Z] / [0.6366 + \beta Z + 1.061\alpha\beta] \} \quad (68)$$

$$\alpha = (C_v/R) - 3/2 \quad (69)$$

$$\beta = 0.7862 - 0.7109\omega + 1.3168\omega^2 \quad (70)$$

$$Z = 2.0 + 10.5T_r^2 \quad (71)$$

Thermal Conductivities of Low-Pressure Gas Mixtures

The theory for calculating the conductivity of for rare-gas mixtures has been worked out in detail (Hirschfelder, et al., 1954; Mason, 1958; Mason and von Ubisch, 1960). In a form analogous to the theoretical relation for mixture viscosity,

$$\lambda_m = \sum_{i=1}^n \frac{y_i \lambda_i}{\sum_{j=1}^n y_j A_{ij}} \quad (72)$$

Where λ_m = thermal conductivity of the gas mixture
 λ_i = thermal conductivity of pure i

y_i, y_j = mole fraction of components i and j
 A_{ij} = a function, as yet unspecified
 $A_{ii} = 1.0$

Mason and Saxena (1958) suggested that A_{ij} in Eq. (72) could be expressed as

$$A_{ij} = \frac{\varepsilon [1 + \lambda_{tri} / \lambda_{trj}] \left(\frac{M_i}{M_j} \right)^{1/4}}{[8 \left(1 + \frac{M_i}{M_j} \right)]^{1/2}} \quad (73)$$

Where M = molecular weight, g/mol
 λ_{tr} = monatomic value of the thermal conductivity

ε = numerical constant near unity

Mason and Saxena proposed a value of 1.065 for ε , and Tandon and Saxena (1965) later suggested 0.85. As used here, $\varepsilon = 1.0$.

Noting that for monatomic gases that $C_v = C_{tr} = 3R/2$

$$\frac{\lambda_{tri}}{\lambda_{trj}} = \frac{\eta_i M_j}{\eta_j M_i} \quad (74)$$

Substituting Eq. (73) into Eq. (74) and comparing with Eq. (67) gives

$$A_{ij} = \varphi_{ij} \quad (75)$$

Where φ_{ij} is the interaction parameter for gas-mixture viscosity.

Thermal Conductivities of Gas Mixtures at High Pressures

Equations (76) to (85) were suggested as a way to estimate the high-pressure thermal conductivity of a pure gas. This procedure may be adapted for mixture given that mixing and combining rules are available to determine T_{cm} , P_{cm} , V_{cm} , Z_{cm} , M_m . Yorizane, et al (1983) have examined this approach and recommend the following:

$$T_{cm} = \frac{\sum_i \sum_j y_i y_j V_{cij} T_{cij}}{V_{cm}} \quad (76)$$

$$V_{cm} = \sum_i \sum_j y_i y_j V_{cij} \quad (77)$$

$$w_m = \sum_i y_i w_i \quad (78)$$

$$Z_{cm} = 0.211 - 0.08w_i \quad (79)$$

$$P_{cm} = Z_{cm} R T_{cm} / V_{cm} \quad (80)$$

$$M_m = \sum_i y_i M_i \quad (81)$$

$$T_{cii} = T_{ci} \quad (82)$$

$$T_{cij} = (T_{ci} T_{cj})^{1/2} \quad (83)$$

$$V_{cii} = V_{ci} \quad (84)$$

$$V_{cij} = \frac{[(V_{ci})^{1/3} + (V_{cj})^{1/3}]^3}{8} \quad (85)$$

Estimation of the Thermal Conductivities of Pure Liquids

In an examination of the thermal conductivities of many diverse liquids, Latini and his coworkers (Baroncini, et al., 1981, 1983, 1984); (Latini and Pacetti, 1977) suggest a correlation of the form:

$$\lambda_L = \frac{A(1-T_r)^{0.38}}{T_r^{1/6}} \quad (86)$$

Where λ_L = thermal conductivity of the liquid, W/(mk)
 T_b = normal boiling temperature (at 1 atm),
 T_c = critical temperature, K
 M = molecular weight, g/mol

$$T_r = T / T_c \quad (87)$$

$$A = \frac{A^* T_b^a}{M^B T_c^Y} \quad (88)$$

Diffusion Coefficient for Binary Gas Systems at Low Pressure

The theory describing diffusion in binary gas mixtures at low to moderate pressures has been well developed. The theory results from solving the Boltzmann equation and the results are usually credited to both Chapman and Enskog, who independently derived the working equation

$$D_{AB} = \frac{3}{16} \frac{(4\pi kT / M_{AB})^{1/2}}{n\pi\sigma_{AB}^2 \Omega_D} f_D \quad (89)$$

Where M_A, M_B = molecular weights of A and B

$$M_{AB} = 2[(1/M_A) + (1/M_B)]^{-1} \quad (90)$$

n = number density of molecules in the mixture

K = Boltzmann's constant

T = absolute temperature
 Ω_D = the collision integral for diffusion, is a function of temperature

σ_{AB} is the characteristic length of the intermolecular force law

f_D is a correction term, which is of the order of unity and n is expressed by the ideal-gas law, Eq. (90) may be written as

$$D_{AB} = \frac{0.00266 T^{3/2}}{P M_{AB}^{1/2} \sigma_{AB}^2 \Omega_D} \quad (91)$$

Where D_{AB} = diffusion coefficient, cm^2/s
 T = temperature, K
 P = pressure, bar

σ_{AB} = characteristic length, $A \Omega_D$ = diffusion collision integral, dimensionless and M_{AB} is defined under eq. (91). To use Eq. (91) some rule must be chosen to obtain the interaction value σ_{AB} from σ_A and σ_B . Ω_D is a function only of $\frac{KT}{\epsilon_{AB}}$.

The simple rules shown below are usually employed:

$$\epsilon_{AB} = (\epsilon_A \epsilon_B)^{1/2} \quad (92)$$

$$\sigma_{AB} = \frac{\sigma_A + \sigma_B}{2} \quad (93)$$

Ω_D is tabulated as a function of KT/ϵ for the Lennard-Jones potential (Hirschfelder, et al., 1954), and various analytical approximations also are available (Johnson and Colver, 1969; Kestin, et al., 1977; Neufeld, et al., 1972). The accurate relation of Neufeld, et al. (1972) is

$$\Omega_D = \frac{A}{(T^*)^B} + \frac{C}{\exp(DT^*)} + \frac{E}{\exp(FT^*)} + \frac{G}{\exp(HT^*)} \quad (94)$$

Where $T^* = KT/\epsilon_{AB}$

A= 1.06036 B=0.15610 C=0.19300 D=0.47635
 E =1.03587 F=1.52996 G=1.76474 H=3.89411

These equations were then used to develop computer program which was then used to investigate the effect of magnetic field on groundwater remediation using steam injection.

IV. DETERMINATION OF RECOVERY EFFICIENCY FOR NUMERICAL SIMULATION

The recovery efficiency (% of contaminant removed) for numerical simulation of groundwater remediation using steam injection with magnetic effects was stated in eqn (95).

$$\% \text{ of contaminant removed} = \frac{\text{Initial NAPL Saturation} - \text{Final NAPL Saturation}}{\text{Initial NAPL Saturation}} \times 100\% \quad (95)$$

V. GEOMETRIC REPRESENTATION OF THE DOMAIN FOR SIMULATION

The geometric configuration of the domain for simulation is shown in Fig. 1. Notably steam injection occurs at A while the contaminant is at B. The magnetic field effect is pressured uniform throughout the domain. The sand box was considered as a three-dimensional system and was discretized into cells with dimensions 1m x 1m x1 m. The measured steam injection rate was used as a flux boundary condition at the injection side of the sand box. At the right hand side of the sand box, a mixed boundary condition was specified that allowed outflow of a phase when the phase pressure exceeded atmospheric pressure and otherwise the boundary was a no-flux boundary. The time step for

groundwater remediation using steam injection with magnetic effect was 50 seconds.

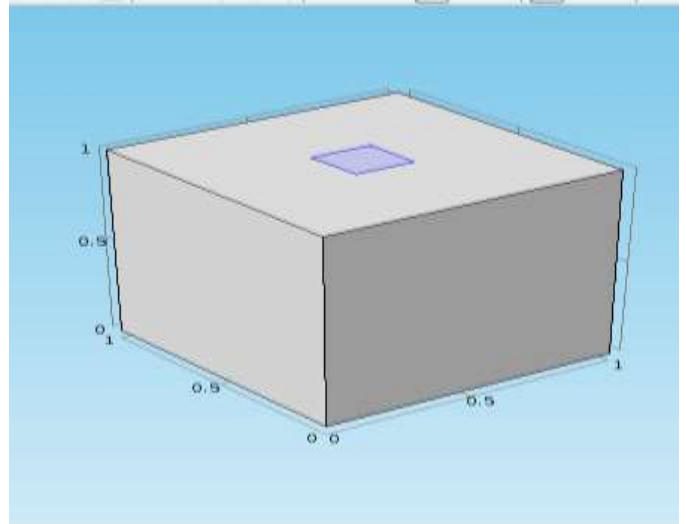


Fig. 1 Geometric Representation of the Domain

VI. DATA ACQUISITION

The soil (coarse sand) properties used to simulate the sand box are stated in Table 1.

Table 1 Soil (Coarse Sand) Properties used to Simulate the Sand Box Experiments

Parameter	Value
Porosity	0.2
Permeability	$1 \times 10^{-16} \text{m}^2$

VII. RESULTS AND DISCUSSIONS

The numerical results for removal of benzene and ethanol from groundwater using steam injection with magnetic effect are reported. The operation practice used and the recovery efficiency in the numerical investigation were listed in Table 2-4. The graphs of recovery efficiency against time are shown in Fig 2-4.

Table 2 Numerical Result for Groundwater Remediation of Benzene and Ethanol at Steam Injection Rate of 0.01m³/s

Numerical no	1	2
Contaminant	Benzene	Ethanol
Operation	Steam Injection	Steam Injection
Recovery Efficiency	71.77%	74.75%

Table 3 Numerical Result for Groundwater Remediation of Benzene at Steam Injection Rate of $0.01\text{m}^3/\text{s}$ and Magnetic Field Strength of 0.2-0.4 T

Numerical no	1	2	3
Magnetic field Strength	0.2 T	0.3 T	0.4T
Contaminant	Benzene	Benzene	Benzene
Operation	Steam Injection with Magnetic Effect	Steam Injection with Magnetic Effect	Steam Injection with Magnetic effect
Recovery Efficiency	82.72%	87.28%	79.28%

Table 4 Numerical Result for Groundwater Remediation of Ethanol at Magnetic Field Strength of 0.2-0.4 T

Numerical no	1	2	3
Magnetic field Strength	0.2 T	0.3 T	0.4 T
Contaminant	Ethanol	Ethanol	Ethanol
Operation	Steam Injection with Magnetic Effect	Steam Injection with Magnetic Effect	Steam Injection with Magnetic Effect
Recovery Efficiency	80.61%	86.22%	84.96%

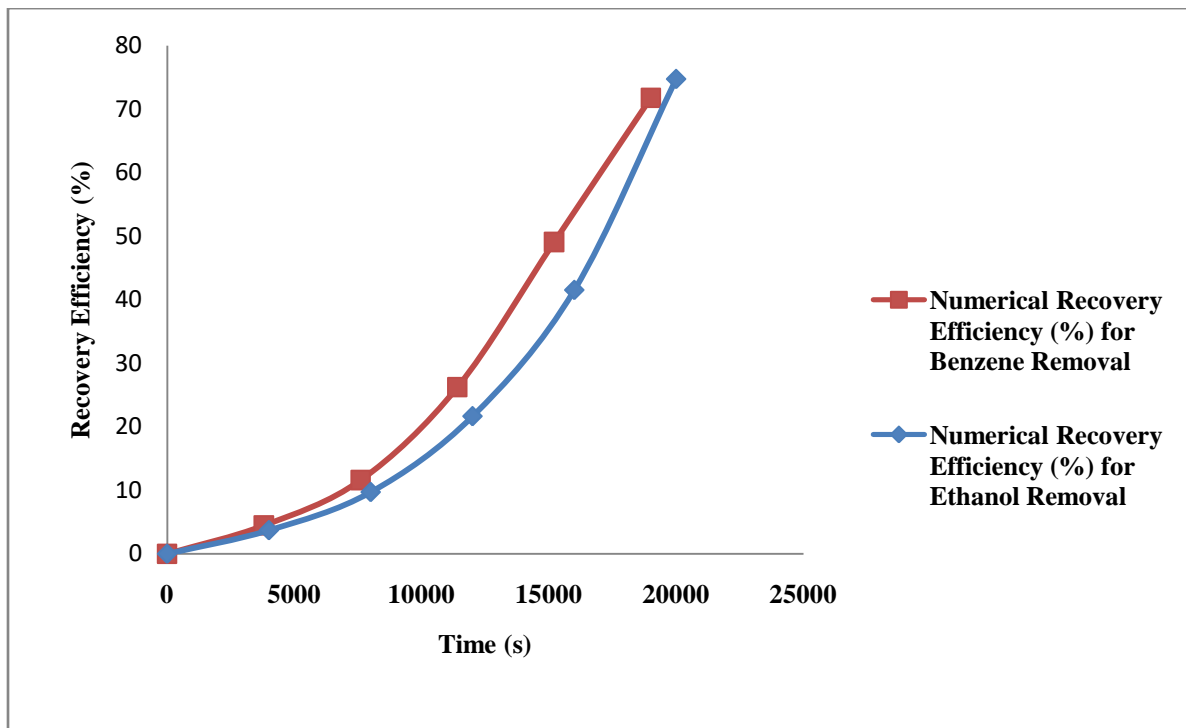


Fig. 2 Benzene and Ethanol Removal efficiency vs Time for Numerical Investigation at Flow Rate of $0.01\text{m}^3/\text{s}$

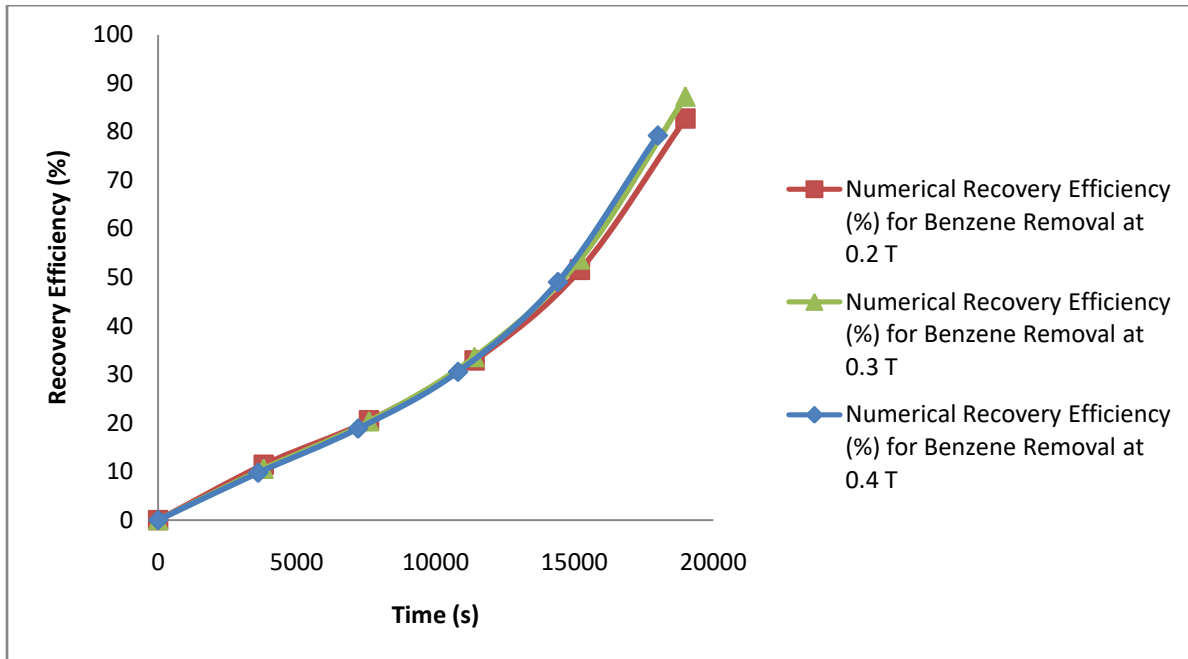


Fig. 3 Benzene Removal efficiency vs Time for Numerical Investigation at Magnetic Field Strength of 0.2-0.4 T

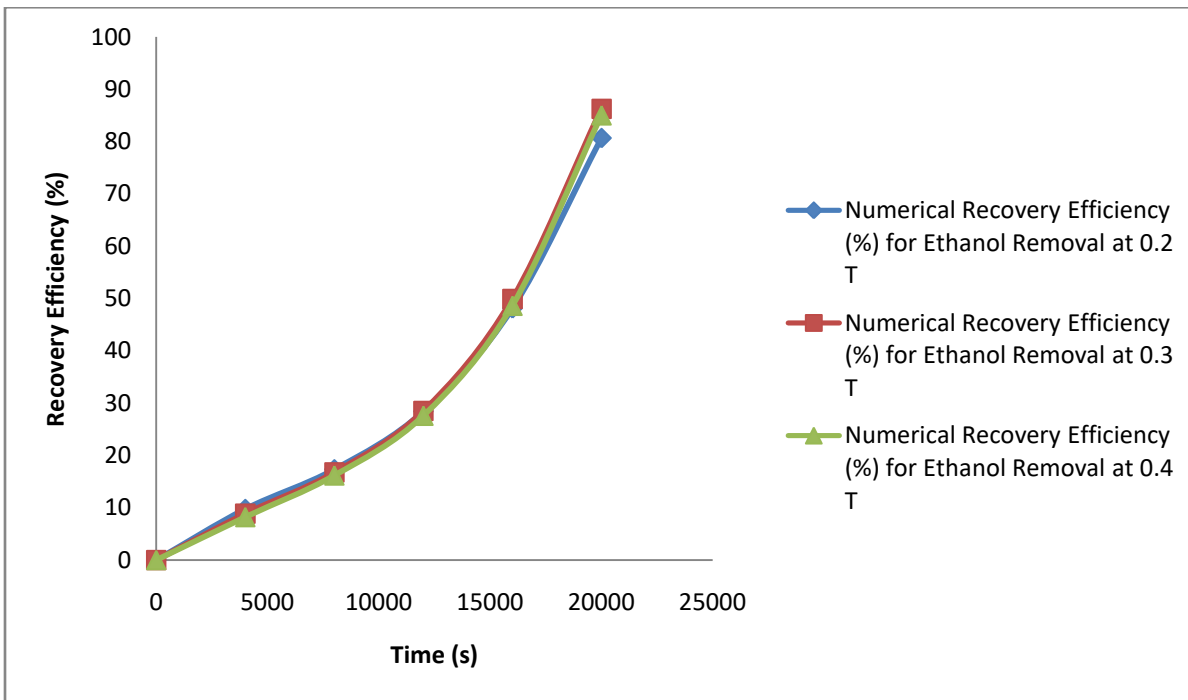


Fig. 4 Ethanol Removal efficiency vs Time for Experimental Investigation a Magnetic Field Strength of 0.2-0.4 T

The numerical results for recovery efficiency of benzene using steam injection only at $0.01\text{m}^3/\text{s}$ yielded 71.77%. The numerical results for recovery efficiency of benzene using steam injection at $0.01\text{m}^3/\text{s}$ and magnetic field of 0.2 T, 0.3 T and 0.4 T yielded 82.72%, 87.28% and 79.28% respectively. The recovery efficiency of benzene increases

with the application of magnetic field strength up to 0.3 T which is the maximum magnetic field strength.

The numerical results for recovery efficiency of ethanol using steam injection at $0.01\text{m}^3/\text{s}$ and magnetic field of 0.2 T, 0.3 T and 0.4 T yielded 80.61%, 86.22% and 84.96%

respectively. The recovery efficiency of ethanol shows the similar trend with benzene as it increases with the application of magnetic field strength up to 0.3 T which is the maximum magnetic field strength. The results thus obtained showed that combined application of steam injection with magnetic field enhance the groundwater remediation.

VIII. CONCLUSION

In this work, a modification of the steam injection technology is presented where the effect of magnetic field on groundwater remediation using steam injection were investigated. The numerical results for recovery efficiency of benzene using steam injection only at $0.01\text{m}^3/\text{s}$ yielded 71.77 % while that of steam injection at $0.01\text{m}^3/\text{s}$ with magnetic effect at 0.2-0.4T yielded 79.28-87.28 %. The numerical results for recovery efficiency of ethanol using steam injection only at $0.01\text{m}^3/\text{s}$ yielded 74.75 % while that of steam injection of $0.01\text{m}^3/\text{s}$ with magnetic effect at 0.2-0.4 T yielded 80.61-86.22 %.

The result demonstrated the ability of steam injection to effectively recover contaminants from the subsurface. The application of magnetic field enhances the removal of pollutant in groundwater and cut down on other remediation process. The study established that combine application of steam injection with magnetic field could appreciably enhance groundwater remediation.

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