Theoretical Investigation of Pneumatic Soil Vapor Extraction

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Abstract

Pneumatic Soil Vapor Extraction (SVE) is a new remediation technique targeting to improve removal of Volatile Organic Compounds from low permeable areas in heterogeneous soil settings in unsaturated zone. In contrast to traditional SVE, in which soil vapor is extracted continuously by a vacuum pump, pneumatic SVE is based on enforcing a sequence of large pressure drops on the system to enhance the recovery from the low-permeable areas to enhance removal from areas subject to diffusion limitation. This technique has been shown to be promising at laboratory scale.

A one-dimensional mathematical model was used to study governing factors and to clarify and quantify the mechanisms responsible for enhanced contaminant removal during this process. From analytical solution it is clear that the gas phase inside low permeable area moves with sinusoidal velocity whose amplitude decreases with depth. Two zones can be distinguished. First in which the gas phase can reach the high permeability area and continuously mixed with clean air, the enhanced removal mechanism is advection. The depth of this zone may range from .05m to .6m. Second is in which there is no net contaminant advection, the enhanced removal mechanism is hydrodynamic dispersion. The hydrodynamic dispersion coefficient may reach a value range from 7 to 700 times the effective molecular diffusion coefficient. In the absence of non-aqueous phase liquid in the first zone, it can be considered a clean conductive zone and impose no transport resistance on the second zone (i.e. mathematically, the upper boundary can be lowered just below the first zone).

The model was tested by comparing its results with experimental results published by a previous study. Overall, comparisons appear to be reasonably good. Investigation shows that pneumatic SVE is promising at field setting. In order for this technique has significant removal enhancement the gas phase permeability in the low permeability region should be at least on order of $1*10^{-12}$ m^2 (1 darcy).

Keywords: Soil vapor extraction, Pneumatic, Unsaturated zone, Mathematical modeling, Volatile organic compounds.

دراسة نظرية لأستخلاص بخار التربة الهوائي

الخلاصة

يعتبر استخلاص بخـار التربـة الهـوائي تقنيـة جديدة تهدف لتحسين ازالـة المـواد العضـوية المتطـايرة مـن المنـاطق ذات النفاذيـة الواطئـة مـن المنطقـة غيـر المشـبعة مـن التربـة. وخلافـا لأستخلاص بخار التربة التقليدي والذي يتم فيه الستخلاص وبصورة مستمرة خلال مضخة تفريغ،

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فأن أستخلاص بخـار التربـة الهـوائي يعتمد علـى احداث سلسلة مـن تخلخلات الضـغط فـي التربـة للمساعدة على ازالة البخار من مناطق التربة المحددة بعملية الأنتشار.

تم استخدام نموذج رياضي ببعد واحد لدراسة العوامل الحاكمة ولتوضيح وزن الاليات المختلفة المسؤولة عن تعزيز ازالة الملوثات خلال هذه العملية. من خلال الحل التحليلي يتبين بأن الطور الغـازي فـي المنـاطق ذات النفاذيـة الواطئـة مـن التربـة يتحـرك بسـرعة جيبيـة تتنـاقص سـعتها مـع العمق. ويمكن تمييز حيزين، الأول والذي يتمكن فيه الغاز من الوصـول الـى المنطقـة ذات النفاذيـة العالية من التربة ويختلط بأستمرار بالهواء النظيف ويكون سبب تعزيز ازالـة الملوثـات فـي هذا الحيز هو حركة الهواء. يتراوح عمق هذا الحيز من 0,05 الى 0,6 متر. في الحيز الثاني والذي لا يوجد فيه صـافي ازاحـة للملوثـات فأن الاليـة المسـؤوله عن تعزيـز ازالـة الملوثـات هـي التشتت الهيدرودينـاميكي، حيث تتراوح قيمة معامـل التشـتت الهيدروديناميكي في هذا الحيز 7 الـى 700 مرة من قيمة معامـل النتشـار الجزيئي الفعال. وبغيـاب الطور السـائل مـن الملوثـات فـي الحيز الأول فبالأمكـان اعتبـاره حيز نظيف موصـل ولايسـبب أي معاوقـة لأنتقـال الملوثـات مـن الحيـز الثـاني (رياضيا، يمكن نقل الحدود العليا الى اسفل الحيز الأول).

تم اختبار النموذج الرياضي بمقارنة نتائجه مع نتائج تجريبية منشوره في بحث سـابق. وبصـورة عامـة كانت المقارنـة جيدة. أظهرت الدراسة بأن تقنية أستخلاص بخـار التربـة مؤملـة. ولكي تكون التقنية ذات تعزيز مـؤثر لأزالـة الملوثـات فأن قيمـة نفاذيـة المنطقـة ذات النفاذيـة الواطئـة يجب أن تكون على الأقل 1×10^{-12} م ^{2} (1 دارسي).

Introduction

Soil vapor extraction (SVE) is the standard in-situ clean-up technique targeting the removal of volatile organic compounds (VOCs) from the unsaturated soil zone. An induced gas flow towards vertical or horizontal wells causes the evaporation of non-aqueous phase liquid (NAPL), the volatilization of the contaminants from the solid particles. Despite the effectiveness and flexibility of SVE technologies, their efficiency and degree of success is controlled by a complex combination of physical, chemical factors. SVE systems characteristically exhibit large initial contaminant exhaust concentrations followed by rapid drop off and low-level removal [1,2].

In high permeable, homogeneous soils low recovery rate may result from air-water mass transfer limitation, diffusion within inter-aggregate water, diffusion within soil water, or rate-limited desorption [3, 4, 5, 1]. While in stratified or heterogeneous soils the removal efficiency of SVE can be significantly reduced, due to air bypassing of low permeable areas. [6,7,8,1]. Thereby advective removal of the contaminant is prohibited within these areas and diffusion is the dominant mechanism responsible for bringing contaminants from the low permeable layer to the advective flow zones [1].

A new vapor extraction technique, pneumatic SVE, is proposed by [1] as an attempt to improve removal of VOCs from low permeable areas in heterogeneous settings. In contrast to traditional SVE, in which soil vapor is extracted continuously by a vacuum pump, pneumatic SVE is based on enforcing a sequence of large pressure drops on the system to enhance the recovery from the low-permeable areas. [1] investigated the pneumatic SVE technique in laboratory using TCE as a model contaminant in a 2-D heterogeneous packs consisted of fine sand lens surrounded by a coarser

sand matrix. When pneumatic venting was used removal rats increased by up to 77%, but the pneumatic SVE cannot entirely overcome the problem of mass limitation. The enhanced removal was hypothesized to be attributed to mixing of contaminated air inside the lens and generation of a net advective transport out of the lens due to air expansion. Pneumatic SVE seemed promising at laboratory scale, so more understanding and theoretical investigation of this process is necessary.

One characteristic of gaseous flow through porous media by which the hypothesized mixing process may be clarified is dispersion, where the differential flow path cause spreading of contaminant. Dispersion is expected to play a role in mechanism responsible for enhanced contaminant removal during pneumatic SVE. Dispersion data is abundant for water flow in the saturated zone but is lacking for air flow in the unsaturated soil. The relative importance of diffusion decreases with increasing interstitial velocity and water content and was, in general, found to be minor compared to, mechanical mixing across a wide range studied by [9].

In this paper a one-dimensional conceptual model is used to clarify and quantify the mechanisms responsible for enhanced contaminant removal during pneumatic SVE process.

Mathematical Development
The major components of the development of the one-dimensional analytical model are presented in detail. These include (1) analytical determination of pressure variation with time and space, (2) formulation of contaminant transport equation, and (3) simplification of the contaminant transport equation using analytical pressure variation obtained in (1).

Analytical determination of pressure variation with time and space
The governing equation of the problem of gas flow in a porous medium is driven from the conservation-of-mass principle as follows [10]:

$$n \frac{\partial P}{\partial t} = \frac{k.k_r}{\mu} \nabla.(P \nabla P) \qquad .....(1)$$

n = soil porosity
k = soil intrinsic permeability (m^2)
k_r = soil relative permeability (-)
μ = gas viscosity (Pa.sec)

This equation is nonlinear. Under circumstance where the gas pressure in the whole system does not vary by a large magnitude (e.g., less than 20% of the mean pressure), Eq.(1) can be simplified to a linear form without causing significant error. The expected magnitude of pressure variation in pneumatic SVE is less than 10% of the mean pressure. Therefore for the purpose of conceptual study, one can start with a linearized governing equation. In case of one-dimensional gas flow, such an equation is [10]:

$$\frac{\partial P}{\partial t} = \alpha \frac{\partial^2 P}{\partial x^2} \qquad ....(2)$$

where

$$\alpha = \frac{k.k_r P_a}{n\mu} \quad (\text{m}^2/\text{sec})$$

P_a = mean pressure (Pa)

The system under consideration is conceptualized as shown in Fig.(1). Uniform sinusoidal pressure fluctuation is assumed at the upper

boundary in the high permeability region. No flow boundary is assumed at the lower boundary:

$$\left(\frac{\partial P}{\partial x}\right)_{x=0} = 0 \dots\dots\dots\dots\dots(3)$$

$$P(l,t) = P_a + A Sin(wt) \dots\dots(4)$$

The analytical solution for problems described by Eq.'s (2)-(4) can be found in work by [11]:

$$P = P_a + A' Sin(wt + \phi) +$$

$$4\pi k' \sum_{n-0}^{\infty} \frac{\left((-1)^{n+1}(2n+1)(4l^2 w)\right)}{16l^4 w^2 + k'^2 \pi^4 (2n+1)^4} *$$

$$Exp\left(-k'(2n+1)^2 \pi^2 t / 4l^2\right)*$$

$$Cos\frac{(2n+1)\pi x}{2l} \dots\dots\dots\dots (5)$$

where

$$A' = A\left\{\frac{Cosh \cdot 2k'x + Cos2k'x}{Cosh \cdot 2k'l + Cos2k'l}\right\}^{\frac{1}{2}} \dots(6)$$

$$\phi = arg\left\{\frac{Coshk'x(1+i)}{Coshk'l(1+i)}\right\} \dots\dots(7)$$

$$k' = \left(\frac{w}{2\alpha}\right)^{\frac{1}{2}} \quad , \quad w = \frac{2\pi}{T_o} \quad \dots (8)$$

T_o = time for complete pressure variation period (sec)

The first term of Eq.(5) is the steady state solution and the second term the transient. The steady periodic solution of the pressure for the system considered is:

$$P(x,t) = P_a + A' Sin(wt + \phi) \dots(9)$$

The quantities A' and ϕ which are the amplitude and phase of the steady pressure oscillation at the point x are functions of the two dimensionless quantities x/l and $k'l$.

If the surface pressure can be represented by the Fourior series

$$\sum_{m=1}^{\infty} a_m Sin(mwt) \quad \dots\dots\dots\dots (10)$$

The steady periodic part of the solution is

$$\sum_{m=1}^{\infty} a_m A_m Sin(mwt + \phi_m) \dots\dots(11)$$

Gas flow velocity, travel time, and flow lines.

After the gas flow equation is solved, interstitial gas velocity can be calculated using Darcy's law

$$v = -\frac{k.k_r}{n\mu}\frac{\partial P}{\partial x} \quad \dots(12)$$

v = interstitial gas velocity (m/sec)

$$v = -\frac{k.k_r}{n\mu}\left[\begin{array}{l}\frac{\partial A'}{\partial x}Sin(wt+\phi)+ \\ A'Cos(wt+\phi).\frac{\partial \phi}{\partial x}\end{array}\right] \dots\dots\dots(13)$$

An analytical expression of v can be obtained from Eq.(13) after substitution from Eq.'s (6) & (7). The interstitial gas velocity is a sinusoidal function of $A, l, k, w, and\ n$.

Any particle in any depth will oscillate up and down near its original position. The oscillatory particle location with time, starting from any point can be calculated using simple

particle tracking technique [12,13]. The technique is initiated by specifying the coordinates of the starting point from which, the velocity is calculated using Eq.(13). This velocity is used to calculate the incremental distance moved by particle through a small increment of time. This incremental travel distance is stored, and the location of the "particle" is updated based on the velocities and the incremental travel time. This procedure is repeated until the "particle" completes the cycle. Maximum distance toward the upper boundary is stored:

$$x_{max} = \int_0^\alpha v(x,t)dt \,|_{max} \,\ldots\ldots\ldots\ (14)$$

As shown in Fig.2, if the "penetration depth" is defined as a distance from upper boundary in which the particle can reach the high permeability zone, and the "enhanced zone" is zone in which the air still remains in the low permeability zone, this penetration depth for any system can be determined.

Fig.'s 3, and 4 show the way in which the penetration depth varies for a range of soil settings, with sinusoidal pressure variation period of 100sec and 1000sec, respectively. While Fig.'s 5, and 6 show the way in which the average velocity of gas just below penetration depth varies for the same soil settings. It is clear that an increase in pressure variation period cause increase in penetration depth accompanied with decrease in gas average velocity in the enhanced zone. In order for this technique creates significant penetration depth the gas phase permeability in the low permeability region should be at least on order of $1*10^{-12}$ m^2 (1 darcy).

Contaminant Transport and fat

After the steady periodic pressure variation with time and space imposed by pressure varying boundary has been determined, it is substituted in Darcy's law to compute the velocity field v of vapor transport as given by Eq.(13). The vapor flux through an unsaturated zone is described by the advection-dispersion equation. In the absence of interphase transfer of contaminant this equation is [2]:

$$\frac{\partial}{\partial t}(nS_a\rho_a x_a) + \nabla \cdot nS_a *$$

$$(\rho_a x_a v - \rho_a D_a^h \nabla x_a) = 0 \,\ldots\ldots\ (15)$$

where

$S_a =$ gas phase saturation

$\rho_a =$ gas phase molar density (mole/m^3)

$x_a =$ contaminant gas phase mole fraction (mole/mole)

$D_a^h =$ Hydrodynamic dispersion tensor (m^2/sec)

for constant $n\,S_a$

$$\frac{\partial}{\partial t}(\rho_a x_a) + \nabla \cdot (\rho_a x_a v -$$

$$\rho_a D_a^h \nabla x_a) = 0 \,\ldots\ldots\ldots\ldots\ (16)$$

or

$$x_a \frac{\partial \rho_a}{\partial t} + \rho_a \frac{\partial x_a}{\partial t} + x_a \nabla(\rho_a v) +$$

$$\rho_a v.\nabla x_a - \rho_a \nabla.D_\alpha^h \nabla x_a -$$

$$D_a^h \nabla x_a.\nabla \rho_a = 0 \,\ldots\ldots\ldots\ldots\ldots(17)$$

Using Darcy's law the last term in Eq.(17) can be shown to be ignored in

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comparison with advection term $\rho_a v.\nabla x_a$. Using Eq.(1), and assume that gas phase behave as an ideal gas with a constant molecular weight. Eq.(17) can be reduced to:

$$\frac{\partial x_a}{\partial t} + v.\nabla x_a - \nabla.D_a^h \nabla x_a = 0 \dots(18)$$

in one-dimensional form:

$$\frac{\partial x_a}{\partial t} + v\frac{\partial x_a}{\partial x} - \frac{\partial}{\partial x}(D_a^h \frac{\partial x_a}{\partial x}) = 0 \,(19)$$

Transport Equation Simplification:

For specific initial and boundary conditions, Eq.(19) can be solved numerically or be simplified as follows:

In system where v and D_a^h are function of time only, Eq.(19) has been solved in a general manner by [14,15]. By transforming variable, Eq.(19) can be reduced to the classical heat equation :

$$\frac{\partial x_a}{\partial \theta} = \frac{\partial}{\partial z}(D_o \frac{\partial x_a}{\partial z}) \quad \dots\dots\dots (20)$$

where

$$\theta = \int_0^t \frac{D(\tau)}{D_o}d\tau \quad \dots\dots\dots\dots (21)$$

$$z = x - \int_0^t v(\tau)d\tau \dots\dots\dots\dots\dots (22)$$

D_o = constant reference value of the dispersion coefficient.
In a system where

$$v(t) = v_{max} \text{Sin}(wt) \quad \dots\dots\dots\dots(23)$$

$z = x$,for $t = \dfrac{2\pi n}{w}$, n = 1, 2, 3, or at

time when pneumatic SVE stops.

and the hydrodynamic dispersion coefficient is given by [16]:

$$D(\tau) = D_{eff} + \alpha_l|v| \quad \dots\dots\dots (24)$$

$\alpha_l = $ soil longitudinal dispersivity
   (m)

Millington and Quirk [17] defined the effective molecular diffusion as coefficient of a gas in porous media as:

$$D_{eff} = n^{\frac{4}{3}} S_a^{\frac{10}{3}} D_m \dots\dots\dots\dots (25)$$

where

$D_m = $ unobstructed vapor phase
    molecular diffusion coefficient
    (m^2/sec)

from Eq.(21)

$$D_o\theta = [D_{eff} + \alpha_l|v|_{av}] \; t \quad \dots\dots (26)$$

$|v|_{av} = $ average of absolute values of velocity (m/sec)

If we define "enhanced diffusion coefficient" as:

$$D_{enh} = D_{eff} + \alpha_l|v|_{av} \quad \dots\dots\dots (27)$$

The monitored values of x_a at

$t = \dfrac{2\pi n}{w}$,   n = 1, 2, 3, ...

or at time when pneumatic SVE stops.

will be governed by

$$\frac{\partial x_a}{\partial t} = \frac{\partial}{\partial x}[D_{enh} \frac{\partial x_a}{\partial x}] \quad \dots\dots\dots (28)$$

Eq.(28) represents a governing equation of contaminant mole fraction in which the transport is purely diffusive with a diffusion coefficient equal to D_{enh}.

Same result can be obtained if we deal with a system in which the

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observer move with velocity $v(t) = v_{max} \text{Sin(wt)}$ relative to the stagnant reference frame. In this case any differential element of width Δx will oscillate in position around its original stagnant position with no change in element width and the governing mechanism of mass transport is diffusion only.

In this study the velocity v is sinusoidal function with amplitude and phase shift vary with position. If we consider a system in which the observer moves with velocity $v(x,t)$ relative to a stagnant reference frame, i.e the transformation will as follows:

$$\theta = \int_0^t \frac{D(x,\tau)}{D_o} d\tau \quad \ldots\ldots\ldots\ldots(29)$$

$$z = x - \int_0^t v(x,\tau)d\tau \ldots\ldots\ldots\ldots(30)$$

The mechanism of mass transport observed in this reference frame is also diffusion only but another variable will sophisticate the problem, that the element width $(\Delta x)_0$ will be variable with time. To evaluate the later effect we must trace $\frac{(\Delta x)_t - (\Delta x)_o}{(\Delta x)_o}$ as a function of time for typical positions in the system. This is done by trace a dynamic distance between two particles initially at positions x and $x + (\Delta x)_0$ using the method previously described. This index was calculated for soil settings considered in Fig.'s 3, 4, 5, and 6. It was a function of time with maximum value of (+.24) and an average value of (+.13). More theoretical work is needed to investigate the effect of this index on contaminant diffusion. However upon ignoring this effect, the contaminant diffusion will be governed by the following equation:

$$\frac{\partial x_a}{\partial t} = \frac{\partial}{\partial x}[D_{enh}(x)\frac{\partial x_a}{\partial x}] \quad \ldots\ldots(31)$$

Recall Fig.2, any particle in the zone above penetration depth can reach the high permeability zone. If we assume that any quantity of air reach the high permeability zone will be replaced by a clean air. This zone can be considered as an advective contaminant transport zone. While the enhanced zone can be considered as a purely diffusive transport zone governed by Eq.(31).

Dispersion data is lacking for air flow in undisturbed unsaturated soil. Many modelers of the transport of volatile organics in unsaturated zone set arbitrary values for longitudinal dispersivity in their works, 1m, 1m, .15m, .1m, and .01m by [18,2,19,20] respectively. Fig.'s 5, 6 show that the of average gas velocity just below penetration depth ranges from 1E-4 m/sec to 1.2E-2 m/sec. The enhanced diffusion coefficient is given by Eq.(27). If the enhancement is defined as the ratio (D_{enh}/D_{eff}), then for a typical contaminant with unobstructed molecular diffusion coefficient of .08E-4 m^2/sec, longitudinal dispersivity of 0.1 m and soil settings covered by Fig.'s 5, 6, this ratio will ranges from 7 to 700.

In the absence of contaminant NAPL in the advective zone the contaminant concentration can approximated to zero and the upper boundary of $x_a = 0$ will be repositioned at a depth equal to the penetration depth as shown in Fig.7.

Model Validation
To test the theory presented in this paper, the model result was verified by compared with published experimental data. Hoier [1] conducted 2D pneumatic experiments in a tank with interior dimensions 106cm*74cm*8cm shown in Fig.8. The tank was packed with air-dried sand. The heterogeneous packs were constructed by inserting a lens of low permeable sand with dimensions 80cm*20cm*8cm. The lens was saturated with water to about .72-.85 water saturation. In one of the pneumatic SVE experiments (pneum2), 60cm^3 of trichloroethylene (TCE) was injected in an approximate homogeneous manner into the lens.

When pneumatic SVE was used, large pressure drops were imposed on the system periodically. Fig.9 shows the air pressure measurements in position A8 and A9 (cf. Fig.8).

Table (1) shows the sequence and durations in which the system is subjected to constant SVE extraction mode and pneumatic SVE mode. Total cumulative extracted TCE mass was measured during venting operation.

Analytical Simulation
Let the physical model of Hoier [1]. experiment be conceptualized as shown in Fig.'s 2 and 7 with pressure in the high permeability region given by:

$$P(pascal) = 90000 + 10000 Sin *$$

$$\left(\frac{2\pi t}{120}\right) \dots\dots\dots\dots\dots\dots\dots\dots(32)$$

The thickness of low permeability zone considered is 10cm, which is equal to the half lens thickness. The low permeability contains a TCE in liquid phase at a concentration of (6.8) mg/cm^3. The experimental conditions are shown in Table (2).

Table.1 Periods of the Pneumatic SVE Experiment [1].

mode	pore volume	time(min)*
constant	2660	6543
pneumatic	1192	4000
pneumatic	770	2580
constant	1179	3036
constant	1169	3010
pneumatic	1635	5477
constant	3786	9843

(*) estimated in this study assuming porosity of the coarse sand of (0.4).

Table.2 Experimental Conditions for the Tank Subjected to Pneumatic SVE [1].

k   intrinsic permeability(m^2) 1.33E-11
k_r relative permeability (-)   0 .03
l soil depth (m)   0.1
T_o period of pressure variation (sec)   120
A   amplitude of pressure variation (Pa)   10000
P_a average pressure (Pa)   90000
μ gas viscosity (Pa.sec)   0.000018
n   air filed porosity 0.21
D_{eff} effective TCE Diffusion coefficient (m^2/sec) 2.0E-8
T^* temperature (C)   25

(*) assumed in this study.

The determined penetration depth (pd), according to calculation procedures described in this study, is (0.015 m). The amplitude of sinusoidal velocity as a function of depth is given by:

$$|v|_{av} (m/sec) = 3.93 * 10^{-4} - .0041 *$$

$$(l - x) \dots\dots\dots\dots\dots\dots\dots\dots(33)$$

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In this system the evaporation front of TCE is continuously move downward with time.

Under the assumptions:

- the equilibrium between contaminant liquid phase and gas phase is described by Raoult's law.
- Dissolution and sorption are ignored.
- Vapor phase behaves as an ideal gas.
- The system is isothermal.

in case of constant extraction SVE, where the contaminant gas transport is assumed to be purely diffusive and the system is at quazi-steady state, the evaporation front position can determined in the following manner:

$$\frac{\overset{\cdot}{m}}{A} = nS_a D_{eff} \frac{C_o}{(l-x)} \quad \dots\dots\dots (34)$$

$$\frac{\overset{\cdot}{m}}{A} = -(\rho_o nS_o)\frac{dx}{dt} \quad \dots\dots\dots (35)$$

$$C_o = \frac{P_v^c M_c}{RT}$$

where

$$\frac{\overset{\cdot}{m}}{A} = \text{evaporation rate per unit area}$$
$$(Kg/m^2. \text{ sec})$$

$C_o = $ contaminant gas phase mass concentration (Kg/m^3)

$\rho_0 = $ contaminant liquid density (Kg/m^3)

$S_o = $ contaminant liquid saturation

$P_v^c = $ contaminant vapor pressure (Pa)

$M_c = $ contaminant molecular weight (Kg/mole)

$R = $ Universal gas constant ($Pa.m^3/K.mole$)

From Eq.'s(34) & (35)

$$-(\rho_o nS_o)\frac{dx}{dt} = nS_a D_{eff} \frac{C_o}{(l-x)} \quad (36)$$

$$x = l - \sqrt{(l-x')^2 + \frac{2nS_a D_{eff} C_o (t-t')}{(\rho_o nS_o)}} \quad .(37)$$

In case of pneumatic SVE and when the contaminant transport in the enhanced zone is governed by Eq.(31). In this equation x_a is the contaminant mole fraction. At evaporation front

$$x_a(t) = \frac{P_v^c}{P_a + A Sin(wt)} \quad \dots\dots\dots (38)$$

Since the period of one pressure cycle is very small relative to the experiment time scale. An averaging procedure for Eq.(38) over one period was done:

$$(x_a)_{av} \approx \frac{P_v^c}{P_a} = \text{constant} \quad , \text{at}$$

evaporation front $\dots\dots\dots\dots(39)$

In the same manner used in deriving Eq.(37), under quazi-steady state, the evaporation front position can determined by the following equation:

$$\int_{l-x'}^{l-x} \int_{pd}^{l-x} \frac{dx}{D_{enh}(x)}.dx = \frac{nS_a C_o (t-t')}{nS_o \rho_o} \dots(40)$$

in which $D_{enh}(x)$ can be given by

Eq.'s(27) and (33)

The contaminant mass removal with time was calculated using Eq.'s

(37) and (40). The longitudinal dispersivity α_l was treated as an adjustable parameter such that a complete removal of TCE from the lens occurs at the end of experimental time shown in table 1. Fig. 10 compares experimental and simulated cumulated TCE mass recovery for pnum2 experiment. The best fit longitudinal dispersivity α_l value was 10.06 cm. Both experimental and predicted results show distinctes increase in slop occurs during the initial part of pneumatic SVE periods. Overall, comparisons appear to be reasonably good. This suggests that the model can capture the main mechanisms responsible for enhanced contaminant removal during pneumatic SVE.

The best fit longitudinal dispersivity α_l value is higher than that presented by [9], (.42 - 2.6 cm), and by [21], (.1 – 5 cm). This higher value may be attributed to high water content in Hoier [1] experiment which is not covered by ranges studied by these researchers and to the different in interstitial velocity range considered. The increasing complexity of the gas pathways in the more complex soils leads to greater spreading of the contaminant front. However [5] considered a value of 7.2 cm in their investigation where intestinal gas velocity was in the range of that in Hoier et al [1]. experiment.

Conclusions

A one-dimensional mathematical model was used to study governing factors and to clarify and quantify the mechanisms responsible for enhanced contaminant removal during this process. From analytical solution it is clear that the gas phase inside low permeable area moves with sinusoidal velocity whose amplitude decrease with depth. Two zones can be distinguished. First in which the gas phase can reach the high permeability area and continuously mixed with clean air, the enhanced removal mechanism is advection. The depth of this zone may range from .05m to .6m. Second is in which there is no net contaminant advection, the enhanced removal mechanism is hydrodynamic dispersion. The hydrodynamic dispersion coefficient may reach a value range from 7 to 700 times the effective molecular diffusion coefficient. In the absence of NAPL in the first zone, it can be considered a clean conductive zone and impose no transport resistance on the second zone (i.e. mathematically, the upper boundary can be lowered just below the first zone).

The model was tested by comparing its results with experimental results published by Hoier et al [1]. Overall, comparisons appear to be reasonably good. Investigation shows that pneumatic SVE is promising at field setting. Investigation show that in order for this technique has significant removal enhancement the gas phase permeability in the low permeability region should be at least on order of $1*10^{-12}$ m^2 (1 darcy).

This study shows that pneumatic SVE is promising at field setting. Further theoretical, numerical, and simple one-dimensional laboratory investigation is necessary for more understanding of this process.

Notations:
SVE   Soil vapor Extraction.
VOC$_S$ Volatile organic compounds

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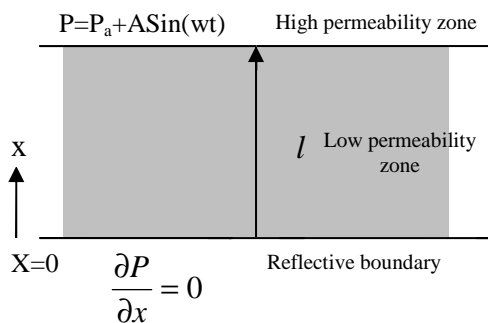
Fig. 1. Flow System Considered in this Study.
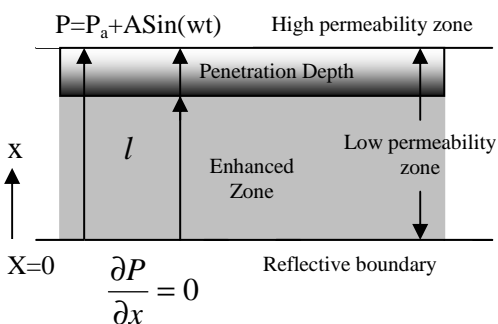
Fig. 2. Flow Zones During Pneumatic SVE
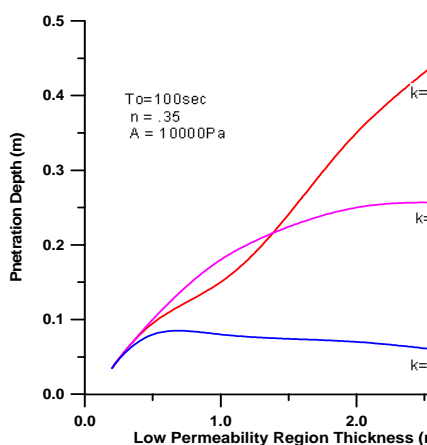
Fig. 3. Penetration Depth for Different Soil Settings (To=100sec).
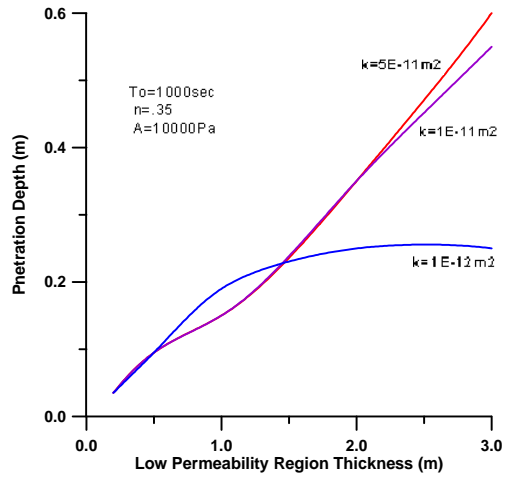
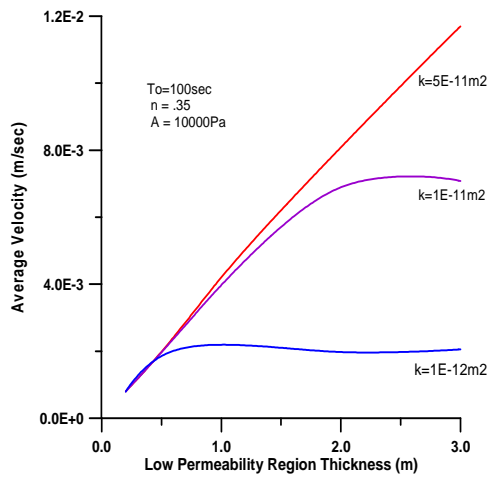**Fig. 4.** Penetration Depth for Different Soil Settings (To=1000sec)

Fig. 5. Average Velocity Just Below
Penetration   (To=100sec).

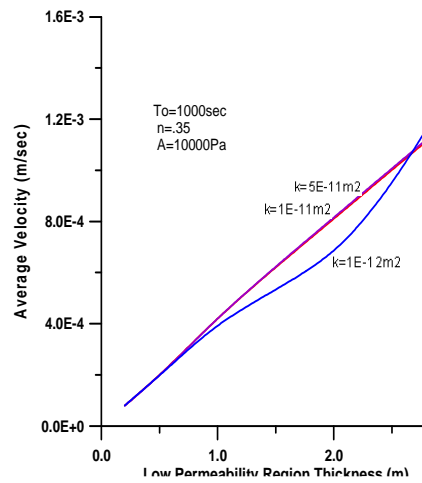**Fig. 6.** Average Velocity Just elow
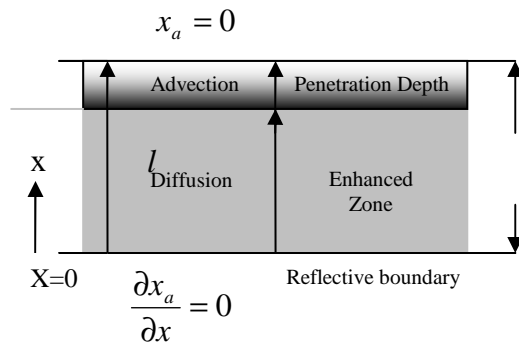Penetration Depth for Different
Soil Settings (To=1000sec).

$$x_a = 0$$

Advection   Penetration Depth

$l_{Diffusion}$ Enhanced Zone

X=0   Reflective boundary

$$\frac{\partial x_a}{\partial x} = 0$$

Fig. 7. Mass Transport Zones During Pneumatic SVE
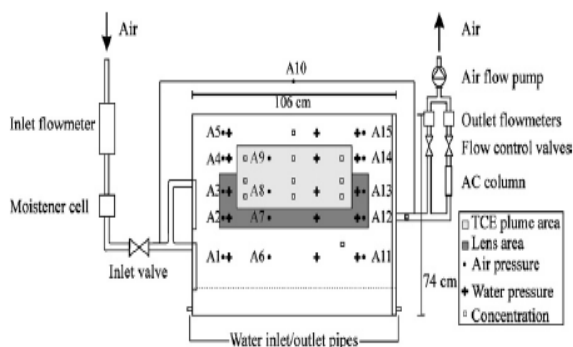
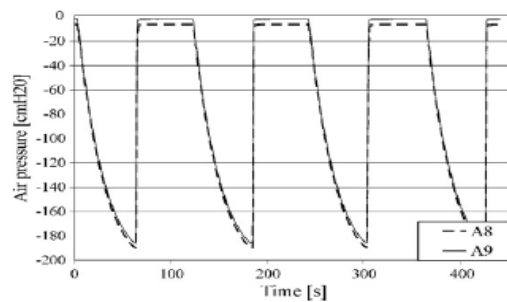**Fig. 8.** Laboratory Setup for 2D Tank Experiment [1].

Fig. 9. Air Pressure During Pneumatic SVE within (A8) and above (A9) the low permeable lens [1].
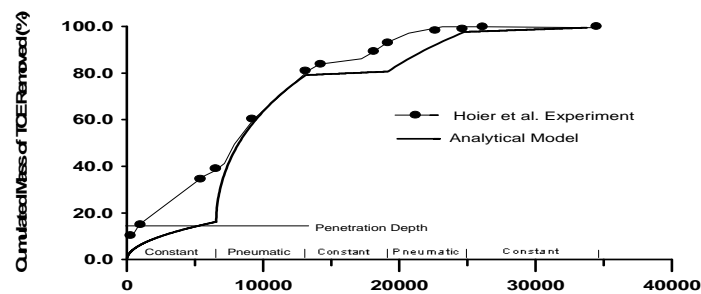

Fig. 10. Cumulative TCE Mass Removal for Pneumatic SVE Experiment.