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Soil Clean Up by *in-situ* Aeration. XII. Effect of Departures from Darcy's Law on Soil Vapor Extraction

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ABSTRACT

Data are presented which indicate that soil vapor extraction (SVE) wells are commonly operated at gas flow rates which are sufficiently high that Darcy's law is not applicable. At Reynolds numbers of the order of 1 or larger, inertial forces as well as viscous forces must be taken into account. This leads to an expression for the wellhead vacuum which is a quadratic function of the molar gas flow rate of the well. Data sets from four wells are examined and found to be in excellent agreement with this quadratic dependence. Equations are given for the scale-up of test data to full-scale SVE wells.

INTRODUCTION

The use of soil vapor extraction (SVE, soil venting, soil vapor stripping, *in-situ* vapor stripping, soil vacuum extraction) is now routine in the remediation of sites having vadose zone contamination with volatile organic compounds (VOCs). The U.S. EPA has recently published a guide (1) and a handbook (2) discussing the technique, Hutzler and his coworkers published a detailed review (3), and this was updated in a recent paper from our group (4). The SVE literature is now quite extensive.

The nature of the SVE technique is such that assessment of its feasibility and SVE system design in any particular application are rather site-specific. These depend on the site geology (depth to water table, pneumatic permeability of vadose zone soils, presence of overlying impermeable structures such as floors or parking lots, heterogeneity of soil, presence of natural or other nonvolatile organics) and on the properties of the contaminants present (vapor pressure, water solubility, partition coefficient on organic carbon, and Henry's constant, all at ambient soil temperature). This has led to considerable interest in the mathematical modeling of SVE for feasibility studies, data interpretation, and system design. Johnson, Kemblowski, Colthart, and their associates have published extensively on this (5–7). Hoag, Marley, Cliff, and their associates at Vapex (8–10) were among the first to use mathematical modeling techniques in SVE. Cho has carried out a quite detailed study in which modeling work was supported by extensive experimental verification (11). Our group has published a number of papers on the mathematical modeling of SVE under a variety of conditions (12, 13, and other papers in this series).

It is common practice (1) in soil vapor extraction treatability studies to determine the pneumatic permeability of the soil by measuring the gas flow rate through a well which is maintained by a given pressure difference. If the system is in the viscous flow regime throughout, so that the gas velocity is proportional to the pressure gradient, this is quite reasonable, and can be done by making measurements at a single flow rate. If, however, there are domains in the system of interest in which the Reynolds number of the fluid is of the order of unity or larger, the simple linear form of Darcy's law no longer holds, and one must take momentum effects into account as well as viscosity (14). The Reynolds number is given by

$$\mathrm{Re} = \rho v d/\mu \qquad (1)$$

where ρ = fluid density
v = fluid velocity
d = characteristic length, of the order of a pore diameter
μ = fluid dynamic viscosity

An expression is given by de Marsily (15) relating the hydraulic gradient to the fluid velocity for the case of an incompressible fluid as one moves into the turbulent flow regime; it is

$$\nabla h = \alpha' U + \beta' U^2 \qquad (2)$$

Here h = hydraulic head
α' = constant
β' = constant
U = fluid velocity

Perry (16) gives a similar relationship for incompressible fluids,

$$\frac{P_1 - P_2}{L} = \frac{\alpha\mu V}{g} + \frac{\beta\rho V^2}{g} \tag{3}$$

where P_1 = absolute upstream pressure
P_2 = absolute downstream pressure
L = length through the porous medium
V = superficial velocity of fluid (based on total cross section)
ρ = fluid density
μ = fluid dynamic viscosity, mass/length time
g = gravitational constant
α = viscous resistance coefficient, length^{-2}
β = inertial resistance coefficient, length^{-1}

as well as an expression for ideal gases which we shall use later.

Thus, we may expect that near the screened section of a well, where there are high pressure gradients, there will be departures from the simple linear form of Darcy's law and that the gas flow rate through the well may not be proportional to the wellhead vacuum. In the following sections we explore this nonlinear effect for an incompressible fluid (assuming all pressures are sufficiently close to 1 atm that the compressibility of air can be ignored) and for an ideal compressible gas. The incompressible approximation lends itself well to analytical treatment, and we close with its application to some experimental data and calculation of some Reynolds numbers for conditions appropriate to SVE well operation.

INCOMPRESSIBLE FLUID APPROXIMATION

Equation (3) is readily rewritten in the limit as $L \rightarrow 0$ as

$$-dP/dL = (A + BV)V \tag{4}$$

where A and B are constants dependent on the characteristics of the fluid and of the porous medium, and L is distance measured in the direction of positive flow. If we consider the flow field of an incompressible fluid moving toward a constant point sink at the origin, we may work in spherical coordinates (r, θ, ϕ) and readily have

$$-V = v_r = -Q/4\pi r^2 \tag{5}$$

and

$$-dP/dL = dP/dr \tag{6}$$

Then Eq. (4) becomes

$$\frac{dP}{dr} = \frac{AQ}{4\pi r^2} + \frac{BQ^2}{(4\pi)^2 r^4} \tag{7}$$

We then integrate Eq. (7) between r_1, the radius of the well's gravel packing, and r_2, a point at some distance from the well where the pressure $P(r_2)$ is essentially 1 atm. This yields

$$P(r_2) - P(r_1) = \frac{AQ}{4\pi}[(r_1)^{-1} - (r_2)^{-1}] + \frac{BQ^2}{3(4\pi)^2}[(r_1)^{-3} - (r_2)^{-3}] \tag{8}$$

For a particular well, A, B, r_1, and r_2 may be regarded as constants (r_2 could generally be set equal to infinity, actually), so that the wellhead vacuum is a simple quadratic function of the gas flow rate. Note that A and B are independent of well geometry and operating conditions; they depend only on the properties of the porous medium and those of air. Later we will see how this permits the scaling up of the results of small test well measurements.

Notice that the smaller the value of r_1 (the radius of the well gravel packing), the larger is the coefficient of Q^2, and the greater is the flow resistance associated with turbulence.

We next turn to the situation where we have axial symmetry—where the well is screened over a substantial length, but where the top of the screened section is well below the surface of the soil. Here we use cylindrical coordinates (r, θ, z). We assume radial flow of the fluid to a length h of the z-axis. For this case it is readily shown that

$$-V = v_r = -Q/2\pi rh \tag{9}$$

and

$$-dP/dL = dP/dr \tag{10}$$

Equation (4) becomes

$$dP/dr = (A + BV)V \tag{11}$$

as before, and substitution of Eq. (9) in Eq. (11) then gives

$$\frac{dP}{dr} = \frac{AQ}{2\pi hr} + \frac{BQ^2}{(2\pi)^2 h^2 r^2} \tag{12}$$

Integration of Eq. (12) between r_1 (the packed radius of the well) and some large value r_2 of the radius at which the pressure is essentially 1 atm then gives

$$P(r_2) - P(r_1) = \frac{AQ}{2\pi h}\log_e(r_2/r_1) + \frac{BQ^2}{(2\pi)^2 h^2}[(r_1)^{-1} - (r_2)^{-1}] \tag{13}$$

As before, we see that for fixed r_1, r_2, A, and B, we get a simple quadratic expression in Q for the wellhead vacuum.

IDEAL GAS LAW APPROXIMATION

If the wellhead vacuum is an appreciable fraction of the ambient pressure (say 0.1 atm or more), the use of the incompressible fluid approximation for air becomes somewhat dubious, and one needs to develop an approach which takes into account the compressibility of air. At pressures of the order of an atmosphere and below, air behaves as an ideal gas to an excellent approximation. Perry (16) gives the following equation for the isothermal flow of an ideal gas:

$$\frac{P_1^2 - P_2^2}{L} = \frac{2\alpha RT\mu G}{Mg} + \left[\beta + \frac{1}{L}\log_e\frac{P_1}{P_2}\right]\left[\frac{2RTG^2}{Mg}\right] \tag{14}$$

Here P_1 = absolute upstream pressure, (mass·length/time^2)/area
P_2 = absolute downstream pressure
L = thickness of the porous medium
G = superficial mass velocity of gas, mass/s·area
g = gravitational constant
μ = dynamic viscosity of air, mass/length·time
M = molecular weight of gas
R = gas constant, mass·length^2/s^2·mol·deg
T = temperature
α = viscous resistance coefficient, length^{-2}
β = inertial resistance coefficient, length^{-1}

In Eq. (14) let us replace L by dL, which will be allowed to approach zero, and P_2 by $P_1 + dP$, where $dP \to 0$ as $dL \to 0$. The log term then becomes

$$-P^{-1}\frac{dP}{dL}$$

and the left-hand side becomes

$$-\frac{dP^2}{dL} = -2P\frac{dP}{dL}$$

With these substitutions it becomes possible to write Eq. (14) as

$$-2P\frac{dP}{dL} = aF + bF^2 - cP^{-1}\frac{dP}{dL}F^2 \tag{15}$$

where F = molar gas flux, moles/time·area
a, b, c = constants dependent on gas characteristics, temperature, and porous medium characteristics

If we consider the case where the well is screened only along a short distance at the bottom, our flow field is that associated with a point sink at the origin; we work in spherical coordinates. This flux in the direction of flow is readily seen to be

$$F = Q/4\pi r^2 \tag{16}$$

If we look at the case where the well is screened along a substantial portion h of its length, and the top of the screened section is well below the surface of the soil, we can work with an axially symmetrical problem. Cylindrical coordinates are appropriate, and the molar gas flux in the direction of flow is

$$F = Q/2\pi hr \tag{17}$$

Replace dP/dL by $-dP/dr$ in Eq. (15), and then solve for dP/dr to get

$$\frac{dP}{dr} = \frac{(aF + bF^2)P}{2P^2 - cF^2} \tag{18}$$

where F is defined as a function of r and of the molar gas flow rate Q by Eq. (16) (spherical symmetry) or (17) (cylindrical symmetry). One then integrates Eq. (18) from some large initial value of r_2 at which $P(r_2) = 1$ atm into a value of r_1 equal to the radius of the well packing, at which point $P = P(r_1)$, the wellhead pressure. Note that if the terms in F^2 are neglected in Eq. (18), one recovers Darcy's law for an ideal compressible gas, which suggests that the constant a can be obtained fairly easily by making measurements at small values of Q. The values of b and c could be obtained by a numerical least squares fit of experimental values of the wellhead pressure to calculated values of $P(r_1)$ over a range of molar flow rates Q, a laborious task.

FITTING TO EXPERIMENTAL RESULTS

In view of the difficulties with fitting the ideal gas model parameters mentioned above, it was decided to focus on the incompressible fluid model. For a particular well, Eq. (8) or (13) can be written as

$$V_w = A_1Q + A_2Q^2 \tag{19}$$

where A_1 and A_2 are the corresponding coefficients in Eq. (8) or (13) and V_w is the wellhead vacuum in atmospheres. The coefficients A_1 and A_2

are readily calculated by the method of least squares, with the following results. Let

$$\sum_{i=1}^{i_{\text{expts}}} Q_i^n V_{wi}^m = SQ^n V_w^m, \qquad n \text{ and } m \text{ integers} \geq 0 \tag{20}$$

Define

$$D = \begin{vmatrix} SQ^2 & SQ^3 \\ SQ^3 & SQ^4 \end{vmatrix} \tag{21}$$

Then

$$A_1 = \begin{vmatrix} SQ^1 V_w^1 & SQ^3 \\ SQ^2 V_w^1 & SQ^4 \end{vmatrix} D^{-1} \tag{22}$$

and

$$A_2 = \begin{vmatrix} SQ^2 & SQ^1 V_w^1 \\ SQ^3 & SQ^2 V_w^1 \end{vmatrix} D^{-1} \tag{23}$$

Equation (19) is easily solved for the gas flow rate Q; the result is

$$Q = \frac{A_1}{2A_2}[-1 + (1 + 4A_2 V_w/A_1^2)^{1/2}] \tag{24}$$

In the limit of small V_w, this yields

$$Q = A_1^{-1}\left[1 - \frac{A_2 V_w}{A_1^2}\right] V_w \tag{25}$$

which shows the relationship to Darcy's law.

EXPERIMENTAL APPARATUS AND PROCEDURE

The first three sets of data were taken from an industrial waste landfill Superfund site in northwestern Pennsylvania. Testing was performed using native topsoil outside of the landfill. The landfill was anticipated to contain VOCs. Some soil may have been disturbed, but that would have occurred over a decade earlier. The pneumatic permeability testing represented the preliminary phase in evaluating SVE as a remedial alternative.

Monitoring wells were installed in a terraced area on the east side of the landfill and along a ridge roughly paralleling the south side. The monitoring wells used in the tests were relatively shallow, reflecting a high and variable water table and installation using a hand auger. In the terraced area they ranged in depth from 4.5 to 5.5 ft, and they were equipped with a 1-ft screened section with 0.020 in. openings. The screened section was surrounded by pea gravel packing approximately 4 in. in diameter and 20 to 24 in. in length. The wells were sealed above the packing with 6 in. of bentonite. Along the ridge south of the landfill the monitoring wells were 5.5 to 6.0 ft deep with screens 1 ft long and having 0.020 in. openings. The packing consisted of 24–36 in. of pea gravel, and the wells were sealed with bentonite. All wells used 2 in. diameter Schedule 40 PVC pipe. A schematic diagram of these wells is shown in Fig. 1.

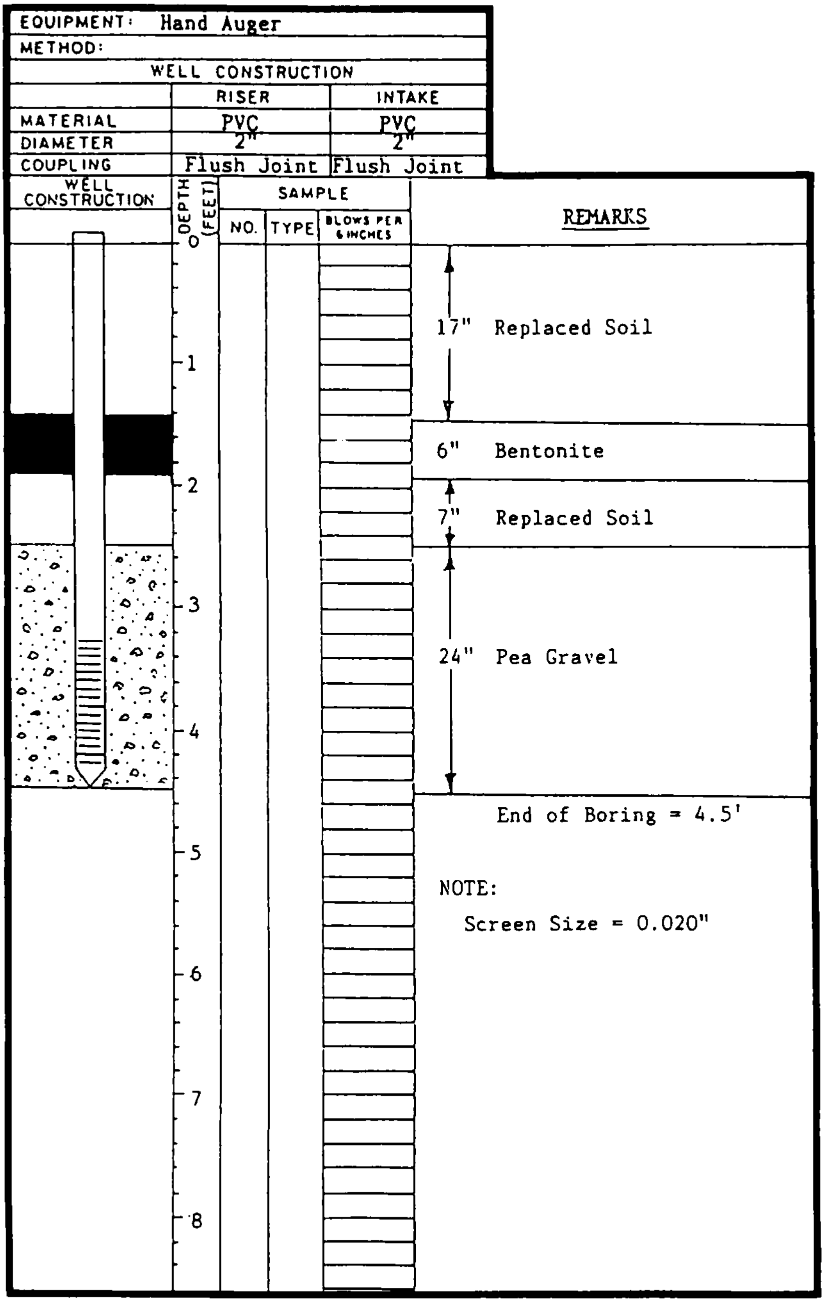
Each of the monitoring wells was tested to see if the zone of influence of the operating extraction well extended to its nearest neighbor. In all instances there was no vacuum observed in the adjacent monitoring wells during operation of the extraction well. Each well was operated at a minimum of three air flows: low, medium, and full throttle. Runs were conducted until the vacuum and flow reached steady-state. Multiple runs were made at some of the wells for *QA*/*QC* purposes.

The fourth and fifth sets of data were taken from a Superfund site in the southern United States. The site had a long history of chemically related activity. Again, pneumatic permeability testing was performed as a part of a preliminary assessment of the potential of SVE for site remediation. Testing was carried out in naturally occurring undisturbed soils consisting of relatively poorly draining silt loam and fine sand loams. Subsoils were silty clay, silty clay loam, and sandy clay. Overall, the area is somewhat poorly drained and has a relatively high and variable water table.

The two monitoring wells were essentially identical; the well pipes extended to a depth of 10 ft and were screened for the bottom 5 ft. The screen had 0.010 in. slots. The wells were constructed of 2 in. Schedule 40 PVC pipe, with a 6.25 in. diameter sand (FX-99) packing. The packing extended from a depth of 4 ft to a depth of 16 ft. The wells were sealed with bentonite. They were approximately 14.3 ft apart. A schematic of these two wells is given in Fig. 2.

Testing was performed by creating a vacuum in one well, the extraction well, and monitoring the change in pressure (vacuum) with time and flow in both the extraction well and the monitoring well. When one well functioned as an extraction well, the other served as the monitoring probe. A U-tube manometer was attached to the monitoring probe to determine resultant vacuum generated as a function of the extraction well operating parameters. The data reported here were collected from one of the wells during two periods about a month apart.

Testing at both sites was performed using the proprietary portable *in-situ* vapor stripping (ISVS) unit developed by Eckenfelder, Inc. The unit is outfitted with a vacuum pump capable of flow rates in the 1 to 10 SCFM



EQUIPMENT: Hand Auger

METHOD:

WELL CONSTRUCTION

	RISER	INTAKE
MATERIAL	PVC	PVC
DIAMETER	2"	2"
COUPLING	Flush Joint	Flush Joint

REMARKS

17" Replaced Soil

6" Bentonite

7" Replaced Soil

24" Pea Gravel

End of Boring = 4.5'

NOTE:

Screen Size = 0.020"

FIG. 1 Diagram of well construction at first site, located in northwestern Pennsylvania.

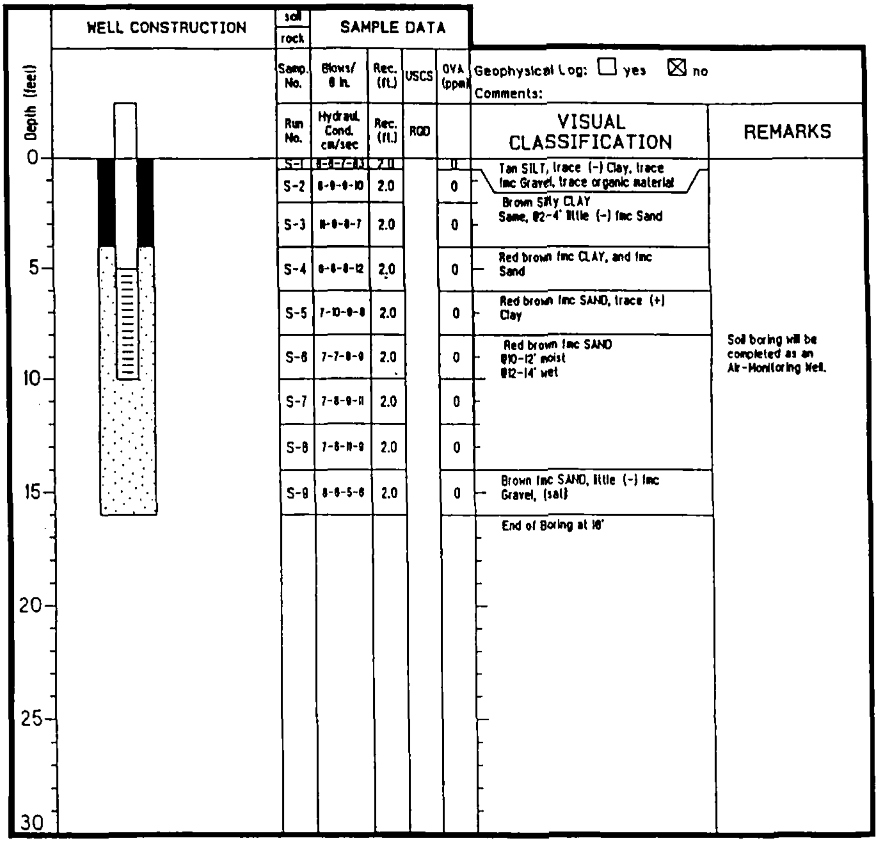


FIG. 2 Diagram of well construction at second site, located in the southern United States.

range and vacua in the 0 to 150 in W.C. (inches of water column) range. The unit contains all necessary display gauges for vacuum and flow readings. The design permits the collection of gas samples for chemical specific analyses or real-time monitoring of total VOC levels. The ISVS unit provided the data reported below on air flow rates and vacuum at the extraction wells.

COMPARISON WITH EXPERIMENTAL DATA

The results of using the incompressible fluid approach to interpret the data from the five sets of permeability tests mentioned above are shown in Tables 1 through 5. The coefficients of determination r^2 obtained with

TABLE 1
First Set of Test Well Data, Pennsylvania Site (see Fig. 3)

Air flow rate (SCFM)	V_w (atm)
1.335	0.005
1.379	0.005
2.850	0.017
2.852	0.018
5.852	0.069
5.852	0.065
5.756	0.069

$V_w = 0.001053Q + 0.001815Q^2$, $r^2 = 0.9964$
Darcy's law yields $V_w = 0.01065Q$, $r^2 = 0.9076$ by least squares fit of $V_w = aQ$
Other correlations determined are:
$V_w = -0.01107 + 0.01301Q$, $r^2 = 0.9530$
$V_w = 0.000115 + 0.0009776Q + 0.001825Q^2$, $r^2 = 0.9971$

the theory were found to be 0.9964, 0.9923, 0.9986, 0.9993, and 0.9944, indicating quite good fits. Coefficients of determination for the linear expressions $V_w = AQ$ were quite significantly lower, as seen in the tables, and coefficients for the general quadratic expression $V_w = A + BQ + CQ^2$ were negligibly improved over those obtained with the theoretical expression which has one less adjustable constant.

TABLE 2
Second Set of Test Well Data, Pennsylvania Site (see Fig. 4)

Air flow rate (SCFM)	V_w (atm)
1.31	0.010
1.31	0.010
2.81	0.052
2.81	0.049
5.67	0.130
5.67	0.130
5.69	0.129

$V_w = 0.0097356Q + 0.002326Q^2$, $r^2 = 0.9923$
Darcy's law yields $V_w = 0.02173Q$, $r^2 = 0.9446$
Other correlations determined are:
$V_w = -0.02621 + 0.02744Q$, $r^2 = 0.9995$
$V_w = -0.02488 + 0.02644Q + 0.00014Q^2$, $r^2 = 0.9996$

TABLE 3
Third Set of Test Well Data, Pennsylvania Site (see Fig. 5)

Air flow rate (SCFM)	V_w (atm)
1.39	0.006
2.90	0.025
5.96	0.081

$V_w = 0.003069Q + 0.001771Q^2$, $r^2 = 0.9986$
Darcy's law yields $V_w = 0.01229Q$, $r^2 = 0.9026$
Other correlations determined are:
$V_w = -0.01968 + 0.01669Q$, $r^2 = 0.9929$
$V_w = -0.006448 + 0.007215Q + 0.001251Q^2$, $r^2 = 1$

TABLE 4
First Set of Test Well Data, Southern U.S. Site (see Fig. 6)

Air flow rate (SCFM)	V_w (atm)
1.92	0.0147
3.85	0.0417
3.79	0.0393
5.03	0.0640
6.02	0.0839
6.02	0.0839

$V_w = 0.004883Q + 0.001513Q^2$, $r^2 = 0.9993$
Darcy's law yields $V_w = 0.01278Q$, $r^2 = 0.9122$
Other correlations determined are:
$V_w = -0.02243 + 0.01735Q$, $r^2 = 0.9879$
$V_w = -0.001741 + 0.005766Q + 0.001411Q^2$, $r^2 = 0.9994$

TABLE 5
Second Set of Test Well Data, Southern U.S. Site (see Fig. 7)

Air flow rate (SCFM)	V_w (atm)
1.73	0.016
4.06	0.044
4.13	0.045
6.03	0.087
6.03	0.0898

$V_w = 0.004295Q + 0.001702Q^2$, $r^2 = 0.9944$
Darcy's law yields $V_w = 0.01335Q$, $r^2 = 0.9028$
Other correlations determined are:
$V_w = -0.02003 + 0.01738Q$, $r^2 = 0.9612$
$V_w = 0.01269 - 0.002363Q + 0.002474Q^2$, $r^2 = 0.9982$

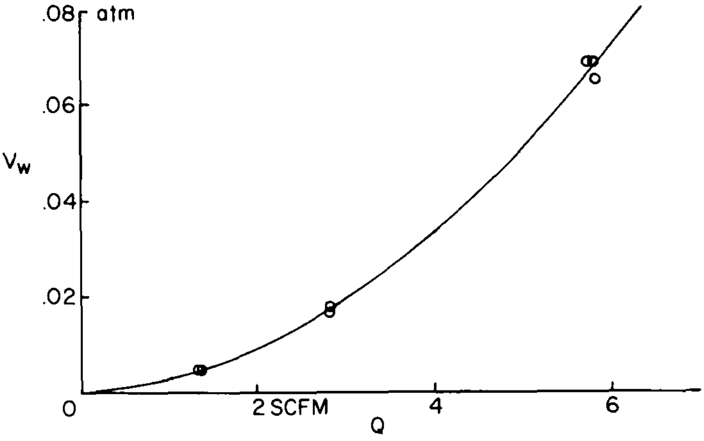


FIG. 3 Plot of well vacuum V_w (atm) versus air flow rate, standard cubic feet per minute (SCFM), for the first data set, Pennsylvania site. The continuous curve is the calculated dependence give by the equation $V_w = 0.001053Q + 0.001815Q^2$, for which $r^2 = 0.9964$. See Table 1.

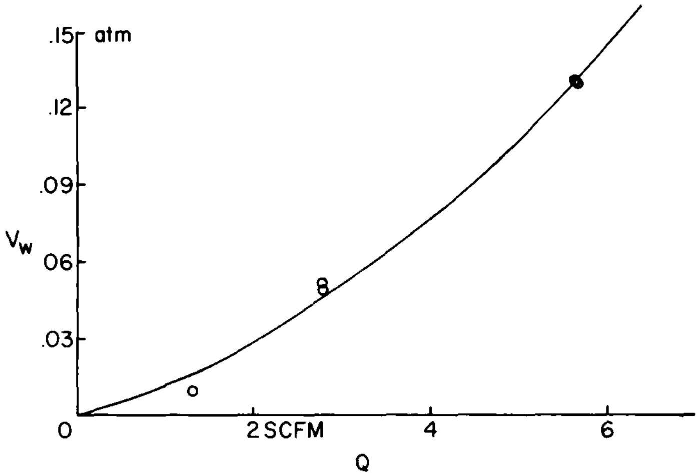


FIG. 4 Plot of well vacuum V_w (atm) versus air flow rate, standard cubic feet per minute (SCFM), for the second data set, Pennsylvania site. The continuous curve is the calculated dependence given by the equation $V_w = 0.009735Q + 0.002326Q^2$, for which $r^2 = 0.9923$. See Table 2.

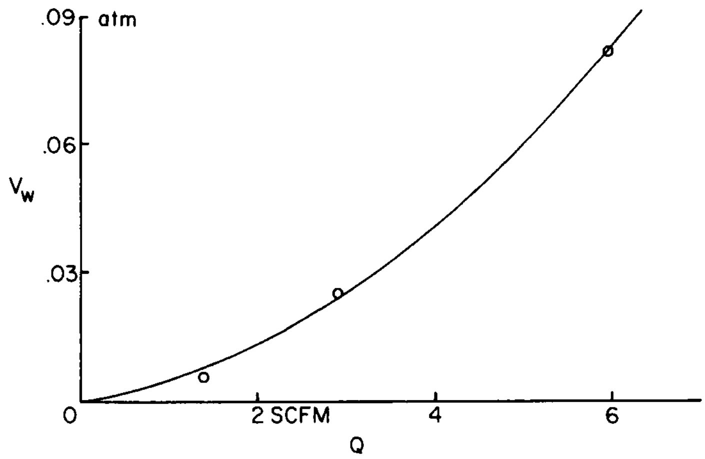


FIG. 5 Plot of well vacuum (V_w) versus air flow rate (SCFM) for the third data set, Pennsylvania site. The curve is the calculated dependence for which the equation is $V_w = 0.003069Q + 0.001771Q^2$, with $r^2 = 0.9986$. See Table 3.

Plots of the experimental points and the theoretical curves for the five sets of data are given in Figs. 3–7. The model appears to provide accurate fits to within the limits of the experimental uncertainty of the data. Also, we see very clearly that these data show large departures from the simple linear Darcy's law (which, if it were operative, would give straight-line

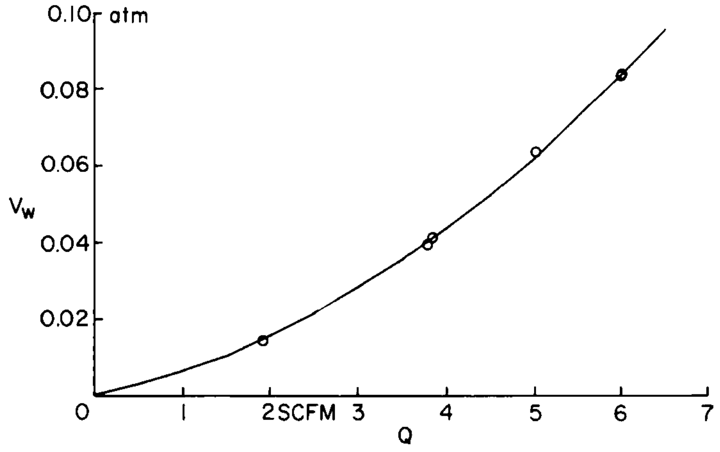


FIG. 6 Plot of well vacuum (V_w) versus air flow rate (SCFM) for the first data set, southern United States site. The curve is the calculated dependence given by $V_w = 0.004883Q + 0.001513Q^2$, with $r^2 = 0.9993$. See Table 4.

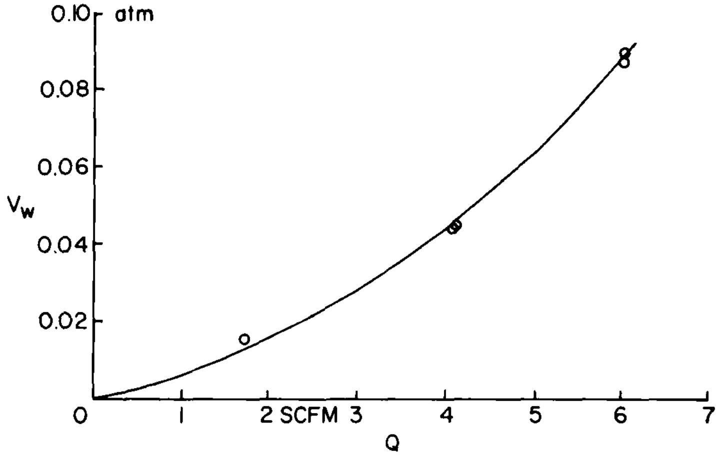


FIG. 7 Plot of well vacuum (V_w) versus air flow rate (SCFM) for the second data set, southern United States site. The curve is the calculated dependence given by $V_w = 0.004295Q + 0.001702Q^2$, with $r^2 = 0.9944$. See Table 5.

plots in Figs. 3–7). Evidently, efforts to calculate Darcy's law permeabilities under these conditions are bound to fail. On the other hand, there is no evidence from these data to indicate that the incompressible fluid model is inadequate. This gives one little incentive to pursue the substantially greater complexities of the ideal compressible gas model.

REYNOLDS NUMBERS

The values of the Reynolds numbers were estimated for some conditions roughly corresponding to our permeability tests and for some corresponding to typical SVE well operation. The Reynolds number is given by Eq. (1),

$$\mathrm{Re} = \rho v d/\mu \tag{1}$$

The gas density ρ is calculated from

$$\rho = \frac{0.3515(1 - V_w/406.9)}{T} \tag{26}$$

where ρ = gas (air) density (g/cm^3)
T = temperature, K
V_w = wellhead vacuum, in. water

The dynamic gas viscosity μ is calculated from

$$\mu = (10^{-5})[0.3008 + 0.072082T - (3.7131 \times 10^{-5})T^2] \qquad (27)$$

where μ = dynamic gas viscosity at temperature T (K) in g/cm·s (poise). Equation (27) results from a least squares quadratic fit to viscosity data for air between 100 and 500 K taken from the *Handbook of Chemistry and Physics* (17); for this fit, $r^2 = 0.999934$.

The gas velocity v is given by

$$v = \frac{471.9Q_{\mathrm{SCFM}}}{2\pi(1 - V_w/406.93)r_w h\nu} \qquad (28)$$

where v = gas velocity at the edge of the well gravel packing, cm/s
Q_{SCFM} = gas flow rate, standard cubic feet per minute
V_w = wellhead vacuum, in. water
r_w = radius of well gravel packing, cm
h = length of screened section of well, cm
ν = soil porosity, dimensionless

TABLE 6
Reynolds Numbers for SVE Wells

Common parameters, all wells:
  Temperature = 15°C
  Soil pore diameter = 0.05 cm
  Soil porosity = 0.3
Common parameters, small-scale test wells:
  Radius of well gravel packing = 2 in.
  Length of well screened section = 12 in.
Small-scale test #1:
  Wellhead vacuum = 4.07 in. water
  Gas flow rate of well = 2 SCFM
  Reynolds number near the well = 1.096
Small-scale test #2:
  Wellhead vacuum = 24 in. water
  Gas flow rate of well = 5 SCFM
  Reynolds number near the well = 2.741
Small-scale test #3:
  Wellhead vacuum = 28.49 in. water
  Gas flow rate of well = 6 SCFM
  Reynolds number near the well = 3.289
Large-scale run:
  Radius of well gravel packing = 6 in.
  Length of well screen section = 36 in.
  Wellhead vacuum = 61 in. water
  Gas flow rate of well = 100 SCFM
  Reynolds number near the well = 6.091

TABLE 7
Densities and Viscosities of Air

Temperature (°C)	Density (1 atm) (g/cm^3)	Dynamic viscosity[a] (g/cm·s) (poise)
5	1.264×10^{-3}	1.748×10^{-4}
10	1.241×10^{-3}	1.773×10^{-4}
15	1.220×10^{-3}	1.799×10^{-4}
20	1.199×10^{-3}	1.824×10^{-4}
25	1.179×10^{-3}	1.849×10^{-4}

[a] Calculated by Eq. (27) from data taken from Ref. 17.

The characteristic length d must be estimated from the soil characteristics; this would be essentially the diameter of the pores which are most important in contributing to the conductivity of the soil to gas.

Reynolds numbers calculated with parameter values roughly corresponding to some of the test well runs are given in the first three cases in Table 6. These are of the order of 1 or larger, indicating that these systems are not in the viscous flow regime. Parameters for the last case in Table 6 were selected to correspond to a typical full-size SVE well. This also yields a Reynolds number which is larger than unity. Given the uncertainty in the characteristic length d, it would be unwise to interpret these Reynolds numbers too closely, but they definitely do not indicate that these wells are being operated in the viscous flow regime. This is consistent with the experimental results shown in Figs. 3–7, which show quite substantial departures from Darcy's law.

The calculation of Reynolds numbers requires the density and dynamic viscosity of air at the wellhead temperature and pressure. Values of these quantities are given in Table 7. Air densities are reported at 1 atm; multiply these figures by $(1 - V_w/406.93)$ to correct these values to the actual wellhead pressure, where V_w is the wellhead vacuum in inches of water.

SCALING UP FROM FIELD TEST DATA

Inspection of Eqs. (8) and (13) allows us to calculate values for the constants A and B in these equations from the values of A_1 and A_2 in Eq. (19) which are obtained from small-scale tests. The values of A and B can then in turn be used to calculate the values of A_1 and B_1 appropriate for wells having different parameters (radius of packing, length of screened section). The relevant expressions are Eqs. (29) and (30) for point sinks (for which $h = r_w$) and Eqs. (31) and (32) for line sinks (for which $h \gg r_w$).

$$A_1 = \frac{A}{4\pi}[(r_1)^{-1} - (r_2)^{-1}] \qquad (n = r_w) \tag{29}$$

$$A_2 = \frac{B}{3(4\pi)^2}[(r_1)^{-3} - (r_2)^{-3}] \qquad (h = r_w) \tag{30}$$

and

$$A_1 = \frac{A}{2\pi h}\log_e(r_2/r_1) \qquad (h \gg r_w) \tag{31}$$

$$A_2 = \frac{B}{(2\pi)^2 h^2}[(r_1)^{-1} - (r_2)^{-1}] \qquad (h \gg r_w) \tag{32}$$

This permits calculation of the behavior of a large, field-scale well from small test well data within the framework of non-Darcian flow which appears to be generally applicable to SVE wells.

CONCLUSIONS

We conclude that soil pneumatic permeability measurements should be carried out over a substantial range of wellhead vacua and gas flow rates, so that the effects of transition and turbulent flow can be taken into account. Failure to consider this factor will usually result in the serious overestimation of gas flow rates when wellhead vacua are increased above the value used in estimating the air permeability of the soil. These effects are by far the most severe in the immediate vicinity of the screened section of the well, where Reynolds numbers are large. Therefore, we expect that if the correct *molar flow rate values* are used in models relying on Darcy's law [such as our own (12, 13, 18), for example], these models should yield correct results. The Darcian models should *not* be relied upon to calculate molar flow rates from wellhead vacua and pneumatic permeability constants, however, because of the strong dependence of the latter on molar gas flux under conditions commonly occurring in soil vapor extraction.

This non-Darcian approach permits scale-up to larger systems almost as easily as does the simpler approach which assumes the validity of Darcy's law for these systems. One simply uses Eqs. (29) and (30) or (31) and (32) to calculate A and B from the test well data, then uses these equations to calculate A_1 and A_2 for the proposed full-scale well(s). These new values are then used in Eq. (19) or (24) to calculate wellhead vacuum as a function of flow rate (Eq. 19) or flow rate as a function of wellhead vacuum (Eq. 24) for the proposed wells.

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