

Infiltration Rate vs. Gas Composition and Pressure in Soil Columns

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Infiltration is influenced by soil gases. Studies have found that CO₂ has a large impact on infiltration. Since CO₂ is highly soluble, soil flooded with it before infiltration has greater saturation and a greater infiltration rate. Our objective was to compare infiltration rates when soil pore gas consisted of (i) CO₂ at atmospheric pressure, (ii) air at atmospheric pressure, and (iii) air at various vacuum levels. A vacuum should, similar to CO₂, reduce encapsulated gas and increase the infiltration rate. Results were that infiltration under 1- to 2-mm constant-head conditions tended to be more rapid at low air pressures. Falling-head infiltration, from 67.8- to 13.8-cm water head, was fastest with CO₂, intermediate with a vacuum that removed all dry air gases, and slowest with air at atmospheric pressure. The final falling-head infiltration rates with CO₂ and vacuum were 1.9 and 1.6 times faster, respectively, than with atmospheric air.

Abbreviations: A, atmospheric air treatment; C, carbon dioxide treatment; V, vacuum treatment.

THE MOVEMENT OF WATER IN soil is influenced by the quantities and types of gases and vapors coincidentally present. Measurements of infiltration and hydraulic conductivity are the most common context in which the effect is observed.

Air encapsulation and *air entrapment* are terms often used to describe situations in which isolated air pockets play an important role in water movement (Christiansen, 1944; Constantz et al., 1988; Fayer and Hillel, 1986; Seymour, 2000; Wang et al., 1997, 1998; Wangemann et al., 2000). The effect of air trapped under an advancing wetting front for homogeneous and two-layered soil profiles was investigated by Latifi et al. (1994), who found that pressure buildup retarded the wetting front. Jarrett and Fritton (1978) reported the same overall effect with laboratory columns of uniform soil and proposed an infiltration model for trapped air conditions.

Carbon dioxide has been shown to alter water movement substantially when it constitutes a large fraction of the soil gas at normal atmospheric pressure (Christiansen et al., 1946; Jarrett and Hoover, 1985; Constantz et al., 1988). Mathematical models have included air as a second phase when solving soil water infiltration and flow problems (van Phuc and Morel-Seytoux, 1972; Wang et al., 1997).

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The effects of soil air are important complicating factors in the basic physics of infiltration (Youngs, 1995).

Standard measurements of hydraulic conductivity (Klute and Dirksen, 1986) consider the aeration conditions in terms of using or not using vacuum saturation and deaeration of the permeating fluid. Techniques for measuring soil air pressure (Fluhler et al., 1986) are available and are of use in evaluating air entrapment and its effects on soil water transient flow.

The works cited above indicate that enrichment of soil gas with CO₂ increases the infiltration rate. The high solubility of CO₂ is believed to be the major reason. This strongly suggests that the infiltration rate should increase as air gas pressure is lowered, providing the rationale for this study. Direct measurements of this relationship have not heretofore been reported.

The objective of this study was, therefore, to measure and compare ponded infiltration rates in laboratory columns with initial soil gas composed of (i) air at ambient atmospheric pressure, (ii) air at various vacuum levels, and (iii) CO₂ at atmospheric pressure. We refer to components of dry air as gases, while the gaseous phase of water is called a vapor. Furthermore, only the major gases of the atmosphere, CO₂, and water vapor are within the scope of this work. The goal for the experiments was to maintain saturation at the soil surface from the initiation of infiltration until the wetting front approached the bottom of the columns. The pressure head of water at the soil surface was maintained either at a small, constant value or allowed to decrease during falling-head experiments.

MATERIALS AND METHODS

Hecla loamy fine sand (sandy, mixed, frigid Oxyaquic Hapludolls), with 670 g kg⁻¹ sand, 250 g kg⁻¹ silt, 80 g kg⁻¹ clay, and 13 g kg⁻¹ organic matter, was used. The soil was packed in 5-cm layers into 2.5-cm-diameter columns to a bulk density of about 1.32 ± 0.01 g cm⁻³ for each layer. Minimum soil column length was 32 cm. All experiments were conducted at 25 to 27°C ambient temperature conditions.

Constant Head

An acrylic tube was used for the constant-head experiments. The packed soil was supported below by a stainless steel screen (½-mm opening) and 1 cm of quartz sand (0.5 mm > diameter > 0.25 mm). A glass tube through a rubber stopper allowed gas outflow from the bottom. The soil top surface was also covered by a stainless steel screen (½-mm opening). The top screen had a 3-mm-diameter solid center to spread water over the soil surface and prevent disturbance by falling water drops. Above the soil was about 3 cm of open space. A rubber stopper with a glass tube for dropping water on the soil surface was inserted into the top. The soil initial water content was 60 g kg⁻¹, corresponding closely to -1.5 MPa (permanent wilting point). The column outlet (bottom) tube passed into the headspace of a 500-mL Erlenmeyer vacuum (side tube) flask ¼ full with 0.35 mol kg⁻¹ NaCl (water potential of -1.5 MPa). A 50-mL burette with a stopcock was connected by a 2-cm length of tubing to the inlet (top) of the soil column.

Infiltration runs were conducted using the burette to manually control water application, maintaining a small depth (optimally 1–2 mm) of ponding on the soil surface. The water used was 0.005 mol L⁻¹ CaSO₄, as suggested by Klute and Dirksen (1986) to minimize dispersion. During atmospheric pressure runs, the vacuum flask side tube and the air space above the soil were open to the atmosphere. During vacuum runs, tubing was attached from the bottom flask side tube to the space above the soil to equalize pressure. Water vapor from the solution (0.35 mol kg⁻¹ NaCl)

maintained the system water potential at -1.5 MPa until the start of infiltration. For reduced-pressure runs, air was evacuated from the system by a vacuum pump. The vacuum was increased in steps of about 15 kPa, each maintained for 15 min or more before the next step-up in vacuum, until the desired vacuum was established. The CaSO_4 solution was stripped of dissolved air using a vacuum pump, with one exception (see below).

The local air pressure was measured with a Hg barometer and the ambient dry air pressure in the system was found by subtracting saturated vapor pressure from the barometric pressure. Consequently, the vacuum level to apply was found from

$$G = B - e_s - P \quad [1]$$

where G is the vacuum gauge reading to be maintained, B is the local barometric pressure, e_s is the saturation water vapor pressure, and P is the dry air pressure desired within the column. Actual water vapor pressure in the system before infiltration is lower than e_s , but very close since -1.5 MPa corresponds to 0.981 relative humidity. A Hg manometer vacuum gauge monitored the system vacuum.

Falling Head

The soil columns for the falling-head experiments were packed in a glass tube that terminated at the bottom end with a tubing connection, allowing escape of gas, similar to the constant-head columns. The soil used, bulk density, initial water content, vacuum establishment, and other conditions for the falling-head experiments were also the same, except as follows. The soil surface was covered by a 2-mm layer of quartz sand (0.5 mm > diameter > 0.25 mm). A stopper with inlet tube was in contact with the sand, so there was no air headspace above the column. A 50-mmol L^{-1} burette without a stopcock, located directly above the soil cylinder and connected to it by flexible laboratory tubing, was used as the falling-head water source. To begin a run, the tubing connecting the burette to the column was unclamped to allow free passage of water to the soil column. The initial head of water was 67.8 cm above the soil surface and the final head, at 50 cm^3 of infiltration, was 13.8 cm.

Three pore gas conditions were used. These conditions were designated A for air at ambient atmospheric pressure, V for vacuum set to gauge reading G (Eq. [1]) at $P = 0$, and C for pure CO_2 at ambient atmospheric pressure. Note that V implies removal of all dry air gases from the system.

Solid CO_2 (dry ice) was used to generate CO_2 gas. It was placed in a flask connected to the flask at the bottom of the soil column by tubing.

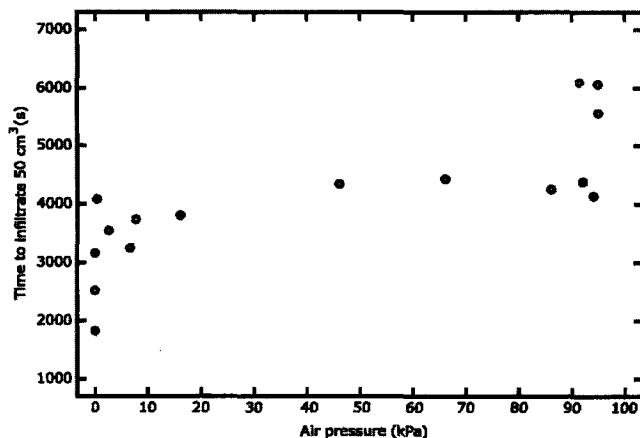


Fig. 1. Time to infiltrate 50 cm^3 of water, 9.87-cm depth, into a Hecla loamy fine sand soil under a 1- to 2-mm constant-head condition at various dry air pressures. The data point adjacent to the @ symbol represents a run with water that was not deaired first.

The gas flowed from the bottom to the top of the column, where it escaped through a one-hole stopper. The CO_2 pressure at the soil column inlet (bottom) was regulated by allowing excess CO_2 to escape at 20-cm depth in a water column. Gas flow through the column was measured at the outflow (top) by directing the outflow into an inverted graduated cylinder initially full of water. Flow of CO_2 was maintained at about $0.3 \text{ cm}^3 \text{ s}^{-1}$ for 1 h minimum before each CO_2 -flooded infiltration run.

Data Collection and Analysis

Time $t = 0.0$ s was set at the first wetting of the soil. Burette readings and corresponding times were recorded until 50 cm^3 of water, or 9.87 cm of water depth for the column, had been released. The vacuum was monitored periodically by Hg manometer.

The SAS procedure GLM (SAS Institute, 1979) was used for ANOVA and means calculation for falling-head infiltration only. Time to accumulate 9.87-cm depth of infiltrated water was the variate used in the statistical analysis. Infiltration rates at 9.87 cm infiltrated were found from the slope of asymptotic lines projected as typical behavior on cumulative infiltration vs. time plots.

RESULTS

Constant Head

Time to infiltrate 9.87 cm of water vs. dry air pressure (Fig. 1) for 15 runs shows a clear indication of shorter times at low pressure (less air), but with large variability. The seven shortest times are at <20 kPa and the seven longest times are at >45 kPa. The seven shortest range from 1823 to 3804 s and the seven longest from 4139 to 6060 s.

At pressures below about 1 kPa, we observed the formation of bubbles (boiling) on the surface and within 1 cm of the soil surface, sometimes at moderate intensity. Some of these bubbles erupted from the soil and visibly clouded the infiltrating water.

Falling Head

Infiltration was fastest with C, intermediate with V, and slowest with A (Fig. 2). Time to infiltrate a 9.87-cm depth of water, 50 cm^3 , was the variate for statistical analysis. Consideration of Fig. 2 leads to the conclusion that A runs had higher variability than the others. Thus, we used a logarithmically transformed variate given by

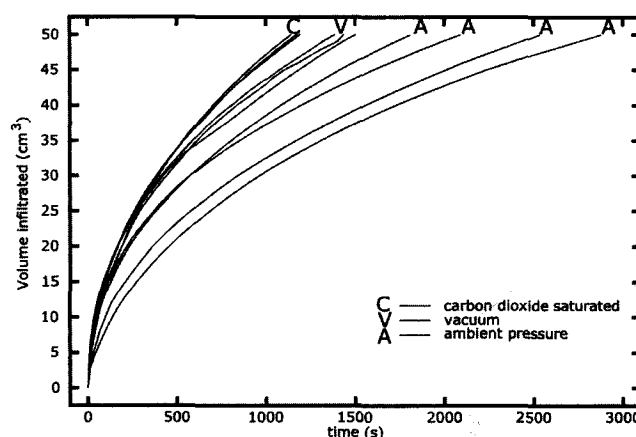


Fig. 2. Water volume infiltrated into Hecla loamy fine sand columns under falling-head conditions vs. time for 10 columns at three distinct soil gas conditions. The three lines showing the most rapid infiltration are with CO_2 flooding (C), the three middle lines are under an airless condition (V), and the four slowest infiltration rate lines (longest times) are for atmospheric air (A) in the soil pores.

Table 1. Analysis of variance for the effect of soil pore gas on falling-head infiltration into Hecla loamy fine sand.

Source	df	Sum of squares	MSE	F
Pore gas	2	20.12	10.06	41.42**
Error	7	1.70	0.24	
Total	9	21.82		

** Significant at the 0.01 probability level.

$$T = \ln(t - 1125) \quad [2]$$

where t is the number of seconds from initiation of infiltration until 50 cm³ (9.87-cm depth) was dispensed from the burette. The ANOVA model for T considered three treatments: A, V, and C. The ANOVA F value (Table 1) indicates a highly significant ($P < 0.01$) treatment effect.

Infiltration rates at the conclusion of the infiltration runs, 9.87-cm depth, were 1.24, 1.00, and 0.64 cm min⁻¹ for C, V, and A. Thus, the final infiltration rate with CO₂ was 1.9 times the atmospheric rate.

DISCUSSION

Constant Head

Despite the clear trend of Fig. 1 indicating faster infiltration with less air, the data are too scattered for a time vs. pressure regression to be very meaningful. Because of the large variability evident in Fig. 1 and the vapor bubble observations noted above, an alternate, falling-head approach with a minimum head of 10 to 20 cm of water was developed. We hypothesize that the vapor bubbles may tend to have somewhat the same effect as trapped air.

Falling Head

The mean T results (Table 2) indicate clear ($P < 0.05$) Duncan's multiple range test differences between atmospheric conditions, A, airless conditions, V, and CO₂ flooding, C; however, this statistical treatment is open to a degree of criticism and interpretation. The treatments were applied in a sequential, observational manner. That is, a conscious decision was made as to what infiltration treatment to apply to the next available packed soil column in light of the accumulated results to that point. Thus, there was not a true randomization, although a column was generally packed before the decision was made about the treatment to be applied. Since the same glass tube was used to pack each column, the process was necessarily sequential.

Regardless of the absence of rigorous randomization, however, the results are clear. They point the way to experiments that can test the effect of the same treatments on other soils with a variety of initial conditions. Ideally, a number of identical columns should be packed at one time and examined for uniformity. Treatments to be applied to each column should then be randomly assigned.

Infiltration rate results (Fig. 2) indicated a faster rate with CO₂ (C) than with air (A), in agreement with Constantz et al. (1988). Our work (loamy fine sand), however, showed that the ratio of the C rate to the A rate (1.9) was far lower than those reported by Constantz et al. (1988), where values of the same ratio were reported as 10.5, 4.7, 4.9, and 5.0 for gravelly loam, sandy loam, sand, and loam, respectively. This indicates that the full range of the CO₂ effect may not have been defined by Constantz et al. (1988) and that the CO₂ effect needs further study.

Infiltration was faster with C than with V. The reason for this is unclear and we are unaware of any previous hypotheses about this topic. It may be that, at very low pressure, spontaneous boiling within soil pores retards liquid flow.

Future work should use a variety of soil textures, structural conditions, and initial water contents. Treatments could include different

Table 2. Duncan's multiple range test for the effect of soil pore gas on falling-head infiltration into Hecla loamy fine sand.

Pore gas	Mean T †	Duncan's‡
Atmospheric	7.029	A
Airless	5.744	B
CO ₂	3.609	C

† The statistic T is $\ln(t - 1125)$, where t is time in seconds from the start of infiltration until accumulation of 9.87-cm water depth.

‡ Groups with different letters are different at $P < 0.05$ by Duncan's multiple range test (SAS Institute, 1979).

head conditions, orientations of the columns (horizontal), and partial pressure of CO₂ and other gases.

CONCLUSIONS

With CO₂ flooding (C), infiltration speeds up beyond that attributable to a reduction of gas entrapment alone, since the airless infiltration (V) treatment should be free of entrapment effects. Thus, infiltration with CO₂ flooding of soil clearly must be influenced by some mechanism that causes it to be more rapid than infiltration in the complete absence of encapsulated air. There is a need to expand the scope of observations of infiltration into CO₂-flooded soil and soil at other soil gas conditions, perhaps with gases of different solubilities and reactivities than CO₂. More information is needed to fully characterize the range of the CO₂ effect. Thus, there is potential, if the CO₂ effect can be understood or at least more thoroughly observed, to advance knowledge about infiltration to a broader basis.

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