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DIVISION S-1—SOIL PHYSICS

An Instrument for *in Situ* Measurements of Soil Moisture Flow and Suction[1]

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ABSTRACT

A soil moisture flux transducer was built and tested in the laboratory under steady-state conditions in a column of Portneuf silt loam soil. Initial data indicate that the instrument may be developed into a useful field research tool. Its principal advantage is that measurements of moisture flow may be made without any prior information concerning the unsaturated hydraulic conductivity of the soil. Rather, one needs to know only a soil moisture convergence factor which is dependent on the state of the soil and the design of the transducer. While this convergence factor is dependent upon the soil moisture content, the dependence appears to be nearly an order of magnitude less than the dependence of hydraulic conductivity on soil moisture content. It may prove possible to develop the unit for installation in the field to provide continuous measurements of the unsaturated soil moisture flow in the tensiometer range with errors no greater than those arising from the natural heterogeneity of the soil.

Additional Key Words for Indexing: **flow transducer, water flow in soil.**

HEAT FLUX transducers have been used for a number of years to detect heat flow in soil. These units measure the temperature gradient across a thin disc of some material with a known and constant thermal conductivity. The heat flux across the disc is then calculated; and since the unit is buried in the ground, the soil heat flux may be inferred. Several soil scientists have suggested that it might be possible to develop a similar transducer to measure moisture flow in soil, see in particular the paper by Richard et al. (1938).[3] Because of the numerous practical applications of such an instrument, a study was initiated along these lines.

The unsaturated soil moisture flow has, in general, been calculated through some application of the so-called Darcy equation

$$J_w = -K \nabla \Phi \quad [1]$$

where J_w is the flow of water in mm per day, K is the unsaturated soil's hydraulic conductivity in mm per day, and $\nabla \Phi$ is the potential gradient in cm of H_2O per cm, including both matrix and gravitational components. Using tensiometers to measure $\nabla \Phi$, it is possible to calculate J_w provided one knows the value of K. Because K decreases sharply as the moisture content drops, it is difficult to apply equation [1] to field problems with any confidence in the accuracy unless a great deal of calibration work has been done so that one knows the relationship between K and soil moisture suction, τ. Even with this knowledge, significant uncertainties may arise as a result of hysteresis and sample changes.

An obvious advantage of a transducer-type instrument is that K need not be known to measure unsaturated soil moisture flow. The principal problem associated with using such a transducer is the uncertainty of convergence of flow lines from the surrounding soil into the transducer. This is diagrammed in Fig. 1. In this case, the transducer is a system of 3 porous plates, cemented into a lucite matrix such that water reservoir is formed on either side of the middle plate. Thus, if the difference in potential across the center plate is measured, the amount of moisture flowing through the transducer is known because the water conductivity of the plate is a given constant. In order to project this information to the rate of moisture flow through the soil surrounding the transducer, the amount of convergence must be known. One may express these relations as

$$J_w' = -k \Delta \phi \quad [2]$$

and

$$J_w = -\frac{k}{f} \Delta \phi = -K \nabla \Phi \quad [3]$$

where J_w' is the water flux through the transducer, $\Delta \phi$ is the potential drop across the center plate, k is the conductivity of the plate, f is the ratio of mean flux through the meter to the mean flux through the soil, and the other symbols are as defined in equation [1].

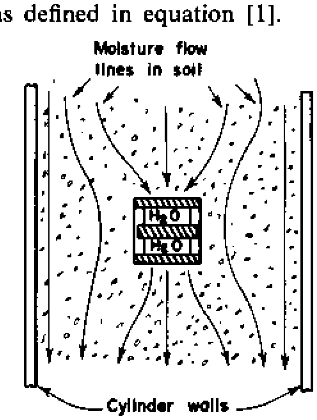

Fig. 1—Cross-sectional view of the first model of transducer in a soil column with a possible configuration of moisture flow lines.

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[3] Richards, L. A., M. B. Russell, and O. R. Neal. 1938. Further developments on apparatus for field moisture studies. Soil Sci. Soc. Amer. Proc. (1937) 2:55–64.

Heat flux transducers are also subject to the convergence problem. They have been mathematically analyzed by several persons. Philip (1961),[4] for example, arrived at the equation

$$f = \frac{\epsilon}{1 + (\epsilon - 1) H} \qquad [4]$$

where f is defined in [3], ϵ is the ratio of meter conductivity to medium conductivity, and H is a constant depending upon the geometry of the meter. In designing a flow meter, it is desirable to have $H \rightarrow 0$, which occurs as the transducer becomes thinner. The amount of convergence of flow from the soil into the meter will approach a limit when the meter conductivity is greater than the conductivity of the surrounding medium; on the other hand, if the conductivity differences are reversed, the value of f would be less than one and the measurement error could approach infinity. Obviously the flow meter should be designed to have a hydraulic conductivity greater than the surrounding soil. Philip presented some sample calculations showing that the meter conductivity could differ from the medium conductivity by a factor of 20 times and still predict the heat flux through the medium with errors not greater than 25%. This was sufficiently encouraging to warrant an attempt at calibrating a transducer for measurement of unsaturated soil moisture flow. While equation [4] is not strictly applicable to unsaturated flow because of the functional relations between K and τ, it appears that the moisture system may favor the use of a transducer due to its "buffering" effect on convergent flow paths.

PROCEDURE

One obvious way to study the behavior of the transducer is to place it in a column of soil in which the moisture tension at each end is controlled. Steady-state moisture flux through the column could then develop and be accurately measured. The moisture flow might then be compared with that predicted by the meter in the center of the column. To make a meaningful calibration with such a system, it is first necessary to find out what size soil column is required so that its boundaries will have a negligible effect upon the convergence of flow into the transducer.

A preliminary investigation was made with an electrical analog study of the problem. This was done in a tray of agar gel approximately 1 m square. A cross-sectional agar model of the meter was placed in the center of the tray. The conductivity of this section was varied by changing the concentration of salt in the water held in the gel. A line source, and a line sink potential were applied across the tray of agar and the equipotential contours were mapped with a voltmeter. While this was only a two-dimensional study and therefore not an exact analog of the system of interest, preliminary results did suggest that the equipotential lines were not noticeably disturbed by the transducer at distances greater than twice the diameter of the transducer.

Concurrently, another preliminary experiment was set up as sketched in Fig. 2. This equipment was held in a controlled temperature box at 25 ± 1C. Steady-state moisture flow through the soil column was established by setting different suctions in the two vacuum jars. When the inflow rate became equal to

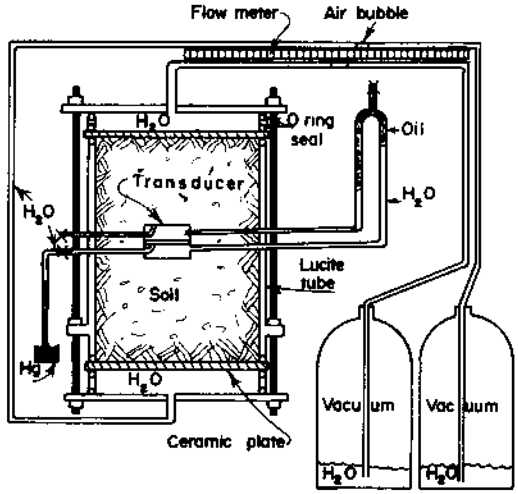

Fig. 2—Cross-sectional diagram of the apparatus used to calibrate the transducer.

the outflow rate, it was assumed that steady-state had occurred. This took from 1 to 4 weeks to achieve, depending upon the soil moisture suction range. As diagrammed in Fig. 2, an oil-water manometer was used to measure the difference in hydraulic head across the center plate in the meter. The oil was kerosene with a small amount of detergent added at the oil-water interface to stop clinging to the sides of the tube. This device has a sensitivity approximately 5 times greater than a water-air manometer system and automatically accounts for the body force of gravity on flow. Nylon tubes were used to connect the water chambers in the transducer to the external pressure manometer and mercury manometer. The system was also arranged such that the lines could be flushed of air when necessary. When the inflow and outflow rates became equal, the potential difference across the center plate, the soil moisture suction in the meter, and the flow rate through the column were recorded (see Table 1). These data were collected from a soil column 19.6 cm in diameter and 21.0 cm long with 3.2-cm radius plates in the transducer. The two outside plates were fritted glass with an effective pore radius of 1 to 2 microns. The center plate was a 6.3 mm piece of 2-bar ceramic.

Although the first model meter produced encouraging results, it did give some problems from occasional leaks in the system under high soil moisture suctions. Therefore, a second instrument was designed and built as diagrammed in Fig. 3. This proved to be much more reliable as far as leaks were concerned and had the additional advantage of making it possible to easily change plates to regulate the conductivity. This unit was fitted with plates 3.9 cm in radius, but otherwise similar to the plates as used in the first model.

To evaluate the effect of column boundaries on flow line convergence, the second type of unit was installed in two systems, each similar to that diagrammed in Fig. 2. The ratio of the cross-sectional area of the soil column to the area of the transducer was 4.2:1 in the smaller column and 9:1 in the larger. The data recorded from these two experiments are pre-

Table 1—Observations made with the first model of transducer; these data were collected in a horizontal column with a cross-sectional area of soil column to transducer ratio of 8.5:1

τ cm Hg	Manometer displacement,* cm	J_w mm/day observed	$k \Delta \varphi$ mm/day	f dimensionless
3.6	2.5	0.3	0.24	0.8
4.8	16.7	1.0	1.59	1.6
7.8	9.0	0.4	0.86	2.2
13.7	3.8	0.25	0.36	1.4
16.5	7.8	0.45	0.74	1.6
17.0	8.0	0.45	0.76	1.7
25.6	3.0	0.20	0.29	1.5
41.4	3.7	0.15	0.35	2.3

* The displacement in cm of the water-oil interfaces as diagrammed in Fig. 2.

[4] Philip, J. R. Theory of heat flux meters. J. Geophys. Res. 66:571. 1961.

Table 2—Observations made with the second model transducer. The hydraulic conductivities are mean values averaged over 21 cm of soil

τ cm Hg	Manometer displacement,* cm	J_w mm/day observed	kΔ σ mm/day	f dimen- sionless	k/f mm/day	K mm/day
		4, 2:1 Area Ratio - Desorption Cycle - Horizontal Column				
3, 6	45. 2	9. 6	11. 3	1, 2	0, 21	1. 1
14, 6	18, 5	2. 0	4. 6	2. 3	0, 11	0, 53
26, 0	12, 1	1. 0	3. 0	3, 0	0, 083	0, 15
25. 5	13, 0	0, 9	3, 3	3, 7	0. 068	0. 17
31, 6	9. 2	0. 7	2. 3	3, 3	0, 076	0, 09
51, 2	7, 6	0. 65	1. 9	2, 9	0, 086	0, 06
		4, 2:1 Area Ratio - Absorption Cycle - Horizontal Column				
27. 1	15, 0	1, 05	3. 7	3. 6	0, 071	0, 08
13, 2	6. 5	0. 55	1, 6	2, 9	0, 086	0, 23
3, 6	13, 8	2. 05	3. 5	1, 7	0, 15	1, 0
		9:1 Area Ratio - Desorption Cycle - Vertical Column				
3. 3	10, 8	1, 55	2, 7	1, 7		
5, 8	8, 5	0, 7	2, 1	3, 0		
8. 4	5, 0	0, 6	1, 2	2, 0		
10. 0	10, 2	0, 9	2, 6	2. 9		
19, 8	5. 7	0. 4	1. 4	3, 5		
25. 7	2, 6	0, 2	0, 65	3. 2		

* The displacement in cm of the water-oil interfaces as diagrammed in Fig. 2.

sented in Table 2. In addition to vertical and horizontal tests and the wetting and drying cycles which are specified in this table, tests were also made with the suction gradient acting both with and against the gravity force in the case of the verical columns and in both from left to right and right to left in the case of the horizontal columns. Since the direction of flow made no difference in the results, it is not specified in Tables 1 and 2.

RESULTS AND DISCUSSION

Because the *f* values shown in Table 2 are nearly the same for the two soil column area ratios, it appears that boundary effects were not important in the convergence of moisture flow into the instrument for any of the data reported. The most important result is the relation between the effective conductivity, *k/f*, of the transducer and the average hydraulic conductivity of the soil as shown in the first section of Table 2. As the soil moisture suction rose from 3.6 to 51.2 cm of mercury, the hydraulic conductivity decreased almost 20-fold. However, the effective conductivity of the transducer changed by a factor of only about 2.5. Moreover, as a result of hysteresis and aging of the soil column, the relationship between conductivity and moisture suction changed by a factor of 2 on the wetting cycle, but values *k/f* showed little change from the results of the desorption cycle.

The *f* values for the first design of transducer, Fig. 1, were less than the *f* values for the second type, Fig. 3. This was caused by the surface area taken up by the brass and O-ring seals in the second type instrument. Only about half of this transducer's total cross-sectional area was available for flow, thus the amount of convergence was increased. It would be desirable to develop a unit with a maximum cross-sectional area available for moisture conduction as diagrammed in Fig. 1, but with the rugged, leak-proof characteristics incorporated in the design of the unit diagrammed in Fig. 3.

As a matter of interest, it may be noted that the instrument described in Fig. 3 was buried in the soil and connected to a pressure transducer and recorder. It was thus possible to continuously measure the unsaturated moisture flow through the soil profile. This setup operated well and gave what appeared to be reasonable responses to irrigation and subsequent drying of the soil surface.

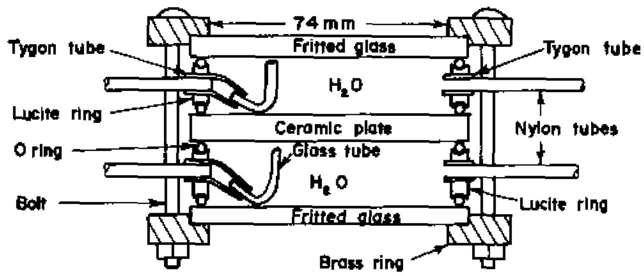

Fig. 3—Cross-section of second model transducer used to collect data in Table 2. The porous plates have a radius of 3.9 cm and the unit has a thickness of about 5 cm.

CONCLUSIONS AND SUGGESTIONS

The preliminary studies reported here indicate that the instrument may be developed into a useful research tool. Its greatest merits are: (i) the soil's hydraulic conductivity need not be known in order to measure unsaturated moisture flow in the field; and (ii) soil moisture convergence is relatively independent of soil moisture content. Problems arising from aging, soil moisture hysteresis, and changes in salt concentration may be largely eliminated. If these preliminary results also are applicable to soils of different textures and composition, it may be possible to develop a unit that can be placed in any soil at any depth to measure unsaturated flow within accuracy limits of possibly ± 30%. This measurement may require only some information on the soil's texture and density rather than the accurate values of the hydraulic conductivity presently needed. Errors involved in this measurement may not be much greater than those arising from the natural heterogeneity of soil in field plots.

There are several problems to be overcome. The unit will only operate at moisture suctions of < 1 bar. However, this is the range in which the bulk of moisture flow occurs. Since the potential differences across the center plate in the meter are small, serious errors can arise if air bubbles develop in the lines leading to the pressure-sensing device on the surface. This hazard can be overcome to an extent by using deaerated water and nylon tubing. However, the system must be flushed occasionally. Perhaps it will be possible to develop a pressure sensor in the transducer itself so that only an electrical signal need be transmitted to the surface. Another disadvantage of the unit is calibration time. Under steady-state conditions as reported in this paper, the calibration is time-consuming and tedious. However, because the *k/f* function appears to be relatively independent of suction, it may be possible to develop a technique for making calibrations under transient soil moisture conditions. This would reduce the time required to fully evaluate the usefulness of the unit in soils of other textures and densities.

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