

Movement of Soil Moisture under a Thermal Gradient

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AN analysis of the flow of soil moisture under a thermal gradient is made for a closed system. This theoretical study indicates that an equilibrium state requires a cyclic transfer of moisture in the soil-water system. Water moving from the warm to the cold side in the vapor phase is returned to the warm side in the liquid phase. This analysis also indicates that the accumulation of moisture on the cold side may be the results of movement of water both as a liquid and as a vapor. However the analysis does not show anything about the relative amounts of moisture in the two.

Using principles from the above analysis, an apparatus for determining quantitatively the amount of water moving in the vapor phase in a steady state process is described. Water vapor moving through the soil system from the warm to the cold side is returned to the warm side through an external capillary tube, in which the rate of movement is measured. A differential equation is presented for estimating the amount of water vapor moving in the system, assuming a molecular diffusion process.

A comparison of results of moisture distributions for circulating and noncirculating systems indicates that moisture movement in the liquid state is not the predominant method of moisture migration for the soil used.

Calculated rates of water movement, assuming a molecular diffusion process, were approximately a sixth of the values of measured rates. Data are presented showing the relationship between the thermal gradient and the quantity of flow. The effect of the dry density and the percent of air-filled void is evident from this data.

● IT is common knowledge that the ability of a highway or airstrip to withstand loading is a sensitive function of the moisture content of the soil. Consequently, the general subjects of moisture movement in soils, moisture accumulation under impervious pavements, and subgrade-moisture control are of prime importance to the highway engineer.

Heat flows continually outward from the earth's surface, and as temperature conditions on the earth's surface fluctuate continuously, temperature gradients of varying magnitude exist within the earth's crust. A number of investigators have shown that moisture movement in soil occurs under the application of a thermal gradient. Thus it is obvious that phenomena of moisture migration under thermal gradients should be understood by the soil engineer.

A review of the literature shows that there

is considerable disagreement as to the nature of the mechanism responsible for this movement. This paper is a progress report on a project initiated in September of 1951 to investigate the mechanism of soil moisture movement under a thermal gradient. Since September of 1953, the project has been enlarged into a broad program designed to study moisture movements in subgrades, soil moisture equilibrium under impervious surfaces, and special methods of subgrade moisture control. The project is being carried on by the Iowa Engineering Experiment Station under sponsorship of the Iowa Highway Commission and the Iowa Highway Research Board.

It should be emphasized that, since this investigation is in its initial phase, the conclusions made by the authors are based on limited data only and should be considered

temporary, pending further results to corroborate the findings.

REVIEW OF LITERATURE

One of the earliest workers to report movements of moisture in soil under a thermal gradient was Lebedeff (12) in Russia. His study included movement of water in both liquid and vapor phases and with and without a temperature gradient.

He presents data to show that if the soil moisture percentage is greater than the hygroscopic coefficient for that soil, then the soil air is at 100 percent relative humidity. He also carried out field experiments to determine upward movements of water during the winter time. Over a period from October 26 to March 1, he recorded soil moisture percentages, evaporation of the water in the soil, and the amount of precipitation. From these readings he computed that a depth of water equivalent to 66.2 mm. per sq. cm. had moved upward to the surface from deeper horizons. Since a temperature gradient existed in the earth's crust, he concluded that the movement upward took place in the vapor phase as a result of a vapor pressure gradient.

Some of the earliest work on soil moisture movement under a thermal gradient in the United States was carried on by Bouyoucos (1, 2) at the experiment station at Michigan State College. His method of procedure was to place soil of different but uniform moisture content in opposite halves of brass tubes 8 inches long and 1½ inches in diameter and then to close both ends with a rubber stopper. The more-moist half of the soil tube was kept at a high temperature and the less-moist half was kept at a lower temperature for a certain length of time, after which the moisture percentages of the two halves of the tube were determined. Any changes in moisture content of the two were attributed to thermal translocation of the soil moisture. Two ranges of temperature were used, 0 C. to 20 C. and 0 C. to 40 C.

He observed that moisture moved from the warm soil to the cold soil at both temperature ranges and that quantity increased regularly and rapidly with increase in moisture content in a variety of different soils until a particular moisture content was reached, and then it decreased with further rise in moisture percentage.

Bouyoucos (1, 2) also attempted to determine the mechanism of soil moisture movement under a thermal gradient. To this end he initially separated the moist from the dry soil in the 8-inch brass tube by an "air ring." The air ring or disk, was ¼ inch thick and was maintained by wire-gauze barriers inserted in the tube. In such an apparatus, presumably, only movement in the vapor phase could take place as the disk broke the capillary contacts. He applied temperature gradients of 40 C. to 0 C. and 20 C. to 0 C. for a period of 8 hours as he had done in previous experiments. He found that the thermal translocation of moisture under this test was only a small fraction of that where capillary contacts were not interrupted. He concluded that the moisture moved as a liquid because water affinity of the soil was greater for the cold than for the warm soil.

Smith (17) was interested in determining the heat conductivity of soil. He noted that translocation of water occurred from the warm to the cold side of a soil specimen and attributed this movement of moisture to a mass movement of water vapor.

Later Smith (18) revised his ideas. He found that when a temperature gradient is applied, a transfer of moisture occurred for a limited range of moisture conditions, and that this movement is confined entirely to the region where the temperature gradient is applied. He criticized the method Bouyoucos used for differentiating between liquid and vapor flow on the basis that the temperature gradient existed primarily across the air space. He set up a new experimental arrangement for determining the relative importance of vapor versus liquid flow and concluded that vapor diffusion was negligibly small. He proposed capillary movement induced by vapor condensation as a mechanism of movement:

Just after a temperature gradient is applied, capillary bodies adjacent to the warm plate are not in equilibrium and [water] begins to evaporate. The excess vapor condenses, to some degree, on the capillary bodies immediately ahead. The resulting body is not in equilibrium and will move by ordinary capillarity into the cell immediately ahead on the cool side. Rings of liquid, only, are left around contact points in the cell vacated. Vapor condensation has served as a trigger to start the process. It should continue until all the liquid, except that left as pendular water in the form of small

rings around contact points, has moved to the cool side of the sample.

Maclean and Gwalkin (13) studied the movement of soil moisture under a thermal gradient and concluded that the mechanism causing the movement was vapor diffusion. They indicate that the time needed to establish equilibrium in a closed system, such as previous investigators had used, was nearly 120 hours for clays, and that it was different for different soils. They assumed that equilibrium conditions were reached when the water-content gradient became such as to give uniform vapor pressure throughout the soil. They gave no vapor pressure data to support this statement.

Trejo (19) investigated movement of soil moisture under a thermal gradient on samples compacted at optimum density. In his apparatus, a soil sample of uniform moisture content 10 cm. long and 2 inches in diameter and enclosed in a lucite cylinder was placed between a steam chamber and a frigid chamber. Moisture movements for rapid and gradual applications of the thermal gradients were determined in natural New Jersey Hagerston soil. He found that the moisture distribution throughout the soil tube after application of the thermal gradient depended upon the rate of application. Gradual application of the gradient caused a linear distribution of moisture throughout the sample with increasing moisture percentages toward the cold end. Rapid application of the gradient gave an S-shaped moisture-distribution curve and sudden application gave a parabolic curve. Moisture accumulated at the cold end with respect to the initial content in all the experiments. He visualized the mechanism of movement as translocation in the liquid phase as a result of the change in water holding affinity caused by temperature differences.

Winterkorn (20) enumerates four possible mechanisms of moisture movement under a temperature gradient: (1) diffusion of water vapor through the pore space under a concentration or partial pressure gradient; (2) diffusion of water in solid solution as observed for hydrophilic membranes separating chambers of different water-vapor pressure; (3) movement as capillary water due to the differences in surface tension at different tempera-

tures; and (4) flow of moisture in the film phase along the internal surface of the porous system due to change in water affinity with change in temperature.

Winterkorn accepted Item 4 (above) as most important, and he developed a theory analogous to electroösmosis using data previously obtained by Baver and himself. Winterkorn compared his theoretically computed coefficient of thermal moisture movement with one he had computed from the data of Maclean and Gwalkin. He concluded that the two coefficients compared favorably. With respect to the movement of moisture in the film phase Winterkorn states:

The physical explanation of the phenomena is that the exchangeable cations possess a greater activity (or are more dissociated) at the cold than at the warm side; they cannot move to the warm side because they are held by negative charges of the mineral surfaces. The only way to decrease this concentration potential is by movement of water from the warm to the cold side.

Gouda and Winterkorn (8) carried out experiments on movement of moisture under a temperature gradient with the aim of investigating similarity between electroösmosis and "thermoösmosis". The soil was placed in lucite cylinders 10 cm. long and 5 cm. in diameter. A temperature gradient was established by bringing one end of the soil tube into contact with a heating coil and the other into contact with ice water. Platinum electrodes were placed in opposite ends of the soil tube to detect any difference in potential.

A summary of their results is as follows; (1) Initial moisture content has considerable effect on the water moved and also on the voltage developed between the two ends. (2) The voltage developed during thermal translocation of moisture was maximum at about the plastic limit. (3) Nearly all water moved in as short a time as 1.33 hours under an average thermal gradient of 3.5 deg. per cm., thus most of the water is moved in the initial stages when the equilibrium is disturbed, and only slight movement occurs during the latter and more extended period. (4) The voltages developed at the beginning of the experiment are very close to or only slightly lower than the maximum.

Croney and Coleman (3) have discussed the movement of soil moisture in road founda-

tions. Using an equation developed by Kelvin, the following equation relating soil vapor pressure to temperature was developed.

$$\frac{T_1}{T_2} = \left(\frac{\zeta_1}{\zeta_2} \right) \left(\frac{\theta_1}{\theta_2} \right) \frac{\text{Log}_{10} \frac{H_1}{100}}{\text{Log}_{10} \frac{H_2}{100}}$$

Where

- θ_1 = Temperature in first state
- θ_2 = Temperature in second state
- ζ_1 = Density of water in the first state
- ζ_2 = Density of water in the second state
- H_1 = Relative humidity in first state
- H_2 = Relative humidity in second state
- T_1 = Surface tension in first state
- T_2 = Surface tension in second state

This equation was used to express the relative humidity of soil at other temperatures in terms of the relative humidity at 20 C. Using known vapor-pressure versus moisture-content curves and the above equation, computed curves show the variation of soil vapor pressure with temperature for the entire soil-moisture-percentage range. These curves show that within the range of moisture content in which thermal translocation of moisture is appreciable, the variation of soil-moisture vapor pressure with temperature is essentially the same as for free water. Also from the Kelvin equation, a derived equation shows the relation of soil moisture tension and temperature. The variation is shown to be small. These authors conclude:

The presence of a temperature gradient in a soil of uniform type creates correspondingly large vapor pressure gradients but only small suction gradients. In this case moisture movement will normally take place in the vapor phase. Experimental work carried out at the road research laboratory indicated that, as the moisture content of a soil is increased, the rate of transfer of moisture associated with a fixed temperature gradient decreases, presumably due to the closure of the soil pores by water in the liquid phase.

Jones and Kohnke (10) studied the movement of soil moisture under a thermal gradient. To start with the movement was assumed to occur primarily in the vapor phase. The equipment used was essentially the same as that used by Bouyoucos (1, 2) except that a more-refined method for maintaining a thermal gradient was used. These investigators

attempted to determine the influence of soil moisture tension on vapor movement of soil water.

Their investigation is summarized as follows: (1) Movement of water increased rapidly with moisture tension up to a certain value, then decreased sharply. (2) The pF (soil-moisture tension) at which moisture movement was initiated and at which maximum movement occurred increased with a decrease in particle size. (3) The volume of unsaturated pores, not their size, seems to govern the soil moisture content at which movement begins. (4) The volume of vapor movement in disturbed soil samples under a given vapor pressure gradient is regulated by the balance of unsaturated pore space, evaporating surfaces, and moisture reserve existing in the soil. (5) Maximum vapor movement occurred at moisture tensions slightly below the wilting point.

Gurr, Marshall, and Hutton (9) have investigated the flow of moisture under a temperature gradient and have concluded that a state of equilibrium cannot be reached without a cyclic transfer of mass. Salts were placed in the cold end as a tracer, and it was found that in all except the wettest and driest soils there was a transfer of salts toward the warm side. This phenomena was explained by the theory that water moved as a vapor from the warm to the cold side, and that when a suitable soil-moisture tension developed, water carrying salts moved in the liquid phase from cold to warm. In these experiments, the maximum net transfer of water from the warm to the cold end occurred in columns in which the initial water contents were approximately a third of the moisture equivalent.

N. E. Edlefsen and W. O. Smith (7) point out that the vapor pressure of soil moisture corresponding to approximately 15 atmospheres of tension is only 0.4 mm. of mercury less than that for free water. This means that the relative humidity for soil moisture tensions less than 15 atmospheres is essentially 100 percent.

Krischer and Ronahltner (11) measured the diffusion coefficient for water in air under a thermal gradient. They give the following value for the diffusion coefficient:

$$K = 0.086 \times \frac{10,000 (T)^{2.3}}{P_0 (273)^{2.3}}$$

Where

P_0 = Total pressure in kilograms per sq. meter

T = Absolute temperature

They also concluded that the amount of water diffusing through a porous media under partial vapor pressure gradient could be expressed as:

$$G_d = - \frac{K}{\mu' R_d T} \frac{P_0}{P_0 - P_s} \frac{dP_s}{dx}$$

Where

G_d = Amount of vapor movement (kg. per sq. m. per hr.)

K = Diffusion coefficient of water in air (sq. m. per hr.)

μ' = A dimensionless factor

R_d = Gas constant for water vapor (meters·kg/kg·°k)

P_0 = Total pressure (kg. per sq. m.)

P_s = Partial water vapor pressure (kg. per sq. m.)

Penman (15) studied the diffusion of carbon disulfide, acetone and carbon dioxide in porous materials including soil. He expressed the diffusion equation for a steady state process as follows:

$$\frac{dq}{dt} = - \frac{D}{B} A \frac{dP}{dl}$$

Where

q = mg. of gas

t = time

D = Diffusion coefficient in porous material

A = Area (cm.²)

l = Length (cm.)

$B = nP$ where n = conc. in mg. per cc. at pressure P .

Upon plotting a curve of the ratio of the diffusion coefficient in porous materials to diffusion constant in air against the volume fraction of air filled voids, a curve valid for all gases tested was obtained. Results indicated that for volume fraction of air-filled voids less than about 0.5 the ratio of $D/D_0 = 0.66S$

Where

D = Diffusion coefficient in porous materials

D_0 = Diffusion coefficient in air only

S = Volume fraction of air filled voids

DeVries (5) computed theoretically the ratio of $D/D_0 = a$, using an electrical model and assuming various shapes of particles. He concluded that in many cases Penman's value of $a = 0.66S$ represent a reasonable estimate, although it may be somewhat low in soils with aggregated structures.

DeVries (4) studied the effect of vapor diffusion under a thermal gradient on heat conductivity. He gives the following equation as valid for molecular diffusion of water vapor in soil pores:

$$q = - \alpha \phi D \gamma \omega \frac{P}{P - P_v} \frac{dP_v}{dt}$$

Where

q = Vapor flux in gm. per sq. cm. per sec.

α = Dimensionless factor depending on the structure

ϕ = Volume fraction of air filled pores

D = Diffusion coefficient of water in air sq. cm. per sec.

$\gamma \omega = \frac{0.289 \times 10^{-3}}{T} = \text{mass of 1 cc. water vapor at 1 mm. pressure and temp. in gm. per cc. per mm. Hg}$

P = Total pressure of moist air = 760 mm. Hg

P_v = Partial pressure of water vapor in mm. Hg

Penman and Schofield (16), assuming that there existed the unique dependence $D/D_0 = 0.66S$, estimated the extent of water movement in soils by molecular diffusion under a thermal gradient. They concluded that even under gradients more extreme than anything likely to arise in nature the transfer was small and that distillation under a temperature gradient was a negligible factor in soil-water movements.

THEORETICAL ANALYSIS

In the following section a capillary model subjected to a thermal gradient is described and analyzed. The analysis is then extended to an unsaturated soil system. Using the principles applicable to these systems procedures are outlined for measuring the amount of moisture moving in the vapor phase and for distinguishing between liquid and vapor movement. Finally a differential equation based on molecular diffusion is presented

which should enable comparisons to be made between measured flow rates and computed values.

This theoretical analysis is initiated by a description of a capillary model subjected to a thermal gradient. The capillary model shown in Figure 1 is believed to be roughly analogous in principle to a closed, unsaturated soil system when the latter is subjected to a thermal gradient. The model consists of a variable radius capillary tube closed at each end and so filled with water that a meniscus is fully developed at each air-water interface. The closed ends of the variable radius capillary tube are connected with each other through a smaller capillary tube as shown in Figure 1.

In this model the capillary moisture in the variable radius capillary is analogous to the capillary moisture in the unsaturated soil system and the variable radius, which allows for different radii of the meniscus, simulates the variation of the curvature of the air-water interfaces in the unsaturated soil as the moisture content fluctuates. The small connecting capillary tube in the model represents the air-filled soil pores in the unsaturated soil system.

Position 1 represents an equilibrium position of the capillary moisture under constant temperature conditions throughout. The vapor pressure in the ends of the variable radius capillary and the small connecting capillary are the same.

If we now subject the capillary model to a temperature gradient, two different processes simultaneously occur. In the first process, the capillary film tends to assume a position represented by Number 2 as a result of change in surface tension with temperature.

Using the following notation:

T_h = Surface tension of water at the hot side.

T_c = Surface tension of water at the cold side.

ΔP_h = Pressure drop across air-water interface at hot side.

ΔP_c = Pressure drop across air-water interface at cold side.

r = Radius of meniscus at constant temperature.

Δr_{c1} = Change in radius of meniscus at cold side resulting from surface tension effects.

Δr_{h1} = Change in radius of meniscus at hot side resulting from surface tension effects.

Δr_{c2} = Change in radius of meniscus at cold side resulting from vapor diffusion effects.

Δr_{h2} = Change in radius of meniscus at hot side resulting from vapor diffusion effects.

ΔP = Pressure drop across air-water interface.

T = Surface Tension of the liquid.

r = Radius of meniscus before application of thermal gradient.

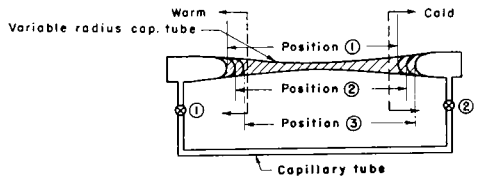
We have $T_c > T_h$ and since $\Delta P = 2T/r$ (assuming a contact angle of zero) $\Delta P_c > \Delta P_h$. Thus the moisture in the capillary tube of variable radius will tend to move from Position 1 to Position 2. At Position 2,

$$\Delta P_c = \Delta P_h$$

where

$$\Delta P_c = \frac{2T_c}{r + \Delta r_c} \quad \text{and} \quad \Delta P_h = \frac{2T_h}{r - \Delta r_h}$$

That is, on the cold side the effect of the increased surface tension on the pressure drop across the air-water interface tends to be offset by the increase in the radius of curvature of the meniscus as moisture movement proceeds toward the cold side. Likewise, on the warm side, the reduction in surface tension tends to be offset by a decrease in the radius of curvature of the meniscus. The overall effect is to cause the capillary moisture to assume a new equilibrium position. As evidenced by the above equations the radius of curvature of the meniscus on the cold side is greater than the radius of the meniscus on the warm side. If this effect is translated into



$$\Delta P = \frac{2T}{r}$$

$$\Delta P_c = \frac{2T_c}{r + \Delta r_{c1}} \quad \Delta P_c = \frac{2T_c}{r + \Delta r_{c1} + \Delta r_{c2}}$$

$$\Delta P_h = \frac{2T_h}{r - \Delta r_{h1}} \quad \Delta P_h = \frac{2T_h}{r - \Delta r_{h1} - \Delta r_{h2}}$$

Figure 1. Capillary model.

moisture contents in a closed unsaturated soil system, the cold side moisture content would be greater than the moisture content on the warm side.

The second process involves vapor diffusion through the small capillary tube. The vapor pressure adjacent to the meniscus on the warm side will be greater than the vapor pressure adjacent to the meniscus on the cold side, and water vapor will diffuse through the small connecting capillary from the warm side to the cold side. Evaporation of the meniscus at the warm side in an infinitesimal time will cause a decrease in its radius of curvature Δr_{2h} and condensation at the meniscus at the cold side will cause an increase in its radius of curvature Δr_{2c} . Thus we will have:

$$P_c = \frac{2T_c}{r + \Delta r_{1c} + \Delta r_{2c}} \quad \text{and} \quad P_h = \frac{2T_h}{r - \Delta r_{1h} - \Delta r_{2h}}$$

Therefore $\Delta P_c < \Delta P_h$ and the capillary moisture will tend to move from the cold to the warm side. If the thermal gradient is maintained on the capillary model, eventually the amount of moisture moving from the warm to the cold side as a vapor will equal the moisture moving from the cold to the warm side as a liquid. This dynamic equilibrium condition in which we have a cyclic movement of moisture is represented by Position 3, Figure 1.

We should note that the increase in the radius of curvature on the cold side over that on the warm side consists of two parts: (1) that increase having to do with the effect of temperature on surface tension and (2) that increase resulting from vapor flow.

The analysis will next be extended to a closed, unsaturated soil system. Such a

system is as shown in Figure 2 if we consider Valves 2 and 3 closed.

Let us assume the existence of a force tending to move water in the liquid phase from a to b when a thermal gradient is established as indicated in Figure 2. Let this force per unit mass of water be designated as F_t . The net result of this movement of moisture would be an accumulation of water in the cold end with respect to the warm end. In like soils, under the same conditions of packing, water will move in the liquid phase from the wetter to the drier soil. That is, there exists a force directed toward the drier soil causing moisture to move in that direction. Let this force per unit mass of water be designated as F_w .

According to the assumption made above, water will move as a liquid under the action of F_t from a toward b when a thermal gradient is established. As moisture accumulates in the cold end, force F_w resulting from a moisture deficiency in the warm end becomes operative, and there is a tendency for water to move from b to a . Thus a point will eventually be reached in which $F_t = F_w$, and movement in the liquid phase will cease. Moisture will have accumulated at the cold side as a result of this process.

Movement in the vapor phase, which occurs simultaneously with the above process, may now be considered. The thermal gradient is effective in providing a vapor pressure difference between a and b . Vapor will thus diffuse through the soil pores from a to b . The resultant evaporation and migration from a and condensation at b result in a total moisture potential difference between these two points, and moisture will tend to flow as a liquid from b toward a . In a manner analogous to the capillary model previously described, a condition will eventually be reached wherein moisture will move in the vapor phase from warm to cold and tend to move in the liquid phase from cold to warm.

The analogy between the capillary model and the unsaturated soil needs some modification, however, at this point. The movement of capillary moisture is a slow process at moisture contents other than those near saturation. Investigators (13) have shown that the capillary conductivity is essentially zero at the field capacity (the amount of water held in the soil after the excess gravita-

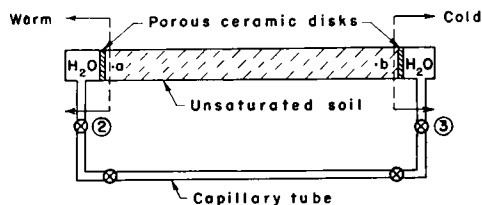


Figure 2. Soil system.

tional water has drained away and after the rate of downward movement has ceased). The result of this is that considerable difference in moisture content is necessary between the cold and warm end before a condition is reached wherein the rate of moisture diffusion in the vapor phase would exactly equal the rate of return flow in the liquid phase.

Advantage can be taken of the above condition to the extent that a quantitative measure of movement in the vapor phase can be obtained. This can be accomplished if we open Valves 2 and 3 shown in Figure 2. The external path from *a* to *b*, consists of the porous disc at *a*, the capillary tube between the end compartments and the porous disc at *b*. The resistance offered to movement by this external path is probably small compared with that which results if movement takes place through the soil pores. The net result is that the moisture potential gradient developing when moisture moves from warm to cold in the vapor phase causes moisture to return in the liquid phase through the external capillary tube. Under these conditions flow in a steady state will eventually be realized and a drop of mercury placed in the capillary tube to trace the rate of flow provides a quantitative measurement of the vapor-flow rate.

One can obtain an indication of the relative importance of film flow versus vapor flow by observing the direction of the movement of moisture in the external capillary at the beginning of an experiment. When a thermal gradient is applied, any movement in the liquid phase toward the cold side could take place just as well in the external capillary. After a period of time, as was pointed out above, that movement would cease. On the other hand, any movement in the vapor phase would cause movement in the external capillary from the cold side to the warm side, and this movement would continue as long as the thermal gradient were applied. Thus the direction of movement in the capillary tube at the beginning of the experiment indicates the relative importance of movement in the liquid phase as compared with movement in the vapor phase.

Since the resistance to flow through the external path is likely small, one is justified in assuming that moisture content differences necessary to maintain this cyclic flow will

also be small. If movement as a liquid were appreciable, one would expect an appreciable accumulation at *b*, even where moisture is allowed to circulate through the external path.

Suppose conditions are provided so that two samples of soil at the same state of packing and moisture content can be run simultaneously, with moisture allowed to circulate through an external tube in one and circulation prohibited in the other. At the end of the run an idealized plot of moisture percent versus distance from warm face might appear as in Figure 3.

Curve *ABC* represents moisture accumulation at the cold side due to movement in both liquid and vapor phases. Curve *DBE* represents the accumulation of moisture at the cold side due primarily to movement in the liquid phase. If the average slope of *DBE* approached zero while that of *ABC* was relatively great, we could conclude that movement of soil moisture under a temperature gradient was primarily accomplished in the vapor phase. If the slope of *DBE* were approximately half that of *ABC*, we could conclude that the movement of soil moisture was equally divided between liquid and vapor phases. In general we could say that if considerable accumulation of moisture in the cold side of the noncirculating system occurs, and if there is only a small accumulation in the cold end in the system where moisture moving in the vapor phase can circulate, then the predominant mechanism of movement is associated with vapor movement.

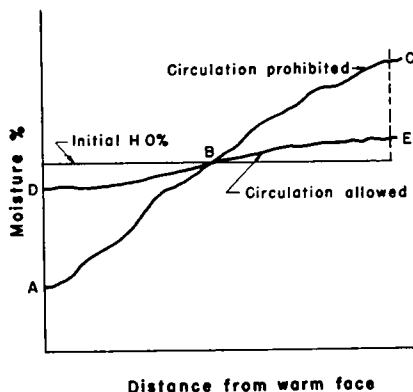


Figure 3. Hypothetical distribution of moisture moving in liquid and vapor phases.

The general equation for a steady state diffusion process in one dimension can be stated as:

$$q = -\frac{D}{dx} \frac{dc}{dx} \quad (1)$$

Where

q = Mass of substance flowing in the x direction in unit time through unit area

D = Diffusion coefficient

$\frac{dc}{dx}$ = Concentration gradient of the substance (Rate of change of mass per unit volume with x)

Now Equation 1 can be written as

$$q = -D \frac{dc}{dp} \frac{dp}{dx} \quad (2)$$

If we assume that water vapor obeys the perfect gas law with P_v = vapor pressure in mm. Hg; V = volume in cc.; m = mass in gm; M = molecular weight in gm.; R , the universal gas constant, in $\frac{\text{mm. Hg cc.}}{\text{gm. mole deg. K.}}$; and T the absolute temperature, then $P_v = \frac{c}{M} RT$ and $\frac{dc}{dp} = \frac{M}{RT}$. Substituting this expression in Equation 2 gives

$$q_v = -\frac{DM}{RT} \frac{dP_v}{dx} \quad (3)$$

Now referring to Figure 1, the total pressure P in the end compartments and the capillary tube must remain constant. This being the case, a partial air-pressure gradient will exist at a given cross-section in the direction opposite to the vapor-pressure gradient at that point. However since the end of the tube towards which the air diffuses is closed, there must be a mass flow of both air and vapor toward the cold side. Let u equal the velocity of mass flow of both air and vapor toward the cold end. The mass per unit volume of vapor

carried along at velocity u is $c = \frac{P_v M}{RT}$.

Therefore the total quantity of vapor passing through a unit cross-section in unit time is $u \frac{P_v M}{RT}$, and the total amount of vapor moving toward the cold side is

$$q_v = -\frac{DM}{RT} \frac{dP_v}{dX} + u \frac{P_v M}{RT} \quad (4)$$

A similar equation can be written for the air movement

$$q_a = -\frac{DM}{RT} \frac{dP_a}{dX} + u \frac{P_a M}{RT} \quad (5)$$

The net flow of air must be zero so that Equation 5 yields

$$u = \frac{D}{P_a} \frac{dP_a}{dX} \quad (6)$$

Now $P_a = P - P_v$

and $\frac{dP_a}{dX} = -\frac{dP_v}{dX}$

Therefore $u = -\frac{D}{P - P_v} \frac{dP_v}{dX}$ (7)

Substituting Equation 7 in Equation 4 gives

$$q_v = -\frac{DM}{RT} \frac{P}{P - P_v} \frac{dP_v}{dX}$$

For the units used here in $\frac{M}{R} = 2.89 \times 10^{-4}$

Letting $\gamma = \frac{2.89 \times 10^{-4}}{T}$

we have $q_v = -D\gamma \frac{P}{P - P_v} \frac{dP_v}{dX}$ (8)

The above derivation follows the derivation for constant temperature diffusion in a vertical glass cylinder when the bottom of the cylinder is covered with water and an air stream applied at the top carries off the excess water vapor (θ). The equation arrived at for constant temperature diffusion is identical with Equation 8 and is known as the Stephan law.

In soils only the air filled voids are available for diffusion and Equation 8 must be modified to some extent. Since diffusion of vapor molecules in soils follows a more tortuous path through the voids, a parameter ($\alpha \phi$) must be included. Equation 8 then becomes

$$q = -\alpha \phi D \gamma \frac{P}{P - P_v} \frac{dP_v}{dX} \quad (9)$$

This is the same equation that DeVries (4) assumes to be valid for diffusion of water vapor in soils.

In summary the quantities in Equation 9 have the following meaning:

- α = A factor depending on structure
 D = Diffusion coefficient of water vapor in air sq. cm. per sec.
 $\gamma = \frac{0.289 \times 10^{-3}}{T} =$ mass of 1 cc. water vapor at 1 mm. pressure and temp. T in gm. per cc. mm. Hg
 P = Total pressure of moist air = 760 mm. Hg
 P_v = Partial pressure of water vapor in mm. Hg
 ϕ = Volume fraction of air filled voids
 x = Coordinate in cm.

We can now write:

$$\frac{dP_v}{dT} \frac{dT}{dx} = \frac{dP_v}{dx} \quad (10)$$

and assuming that water vapor behaves as a perfect gas, the Clapeyron equation becomes:

$$\frac{dP_v}{dT} = \frac{18LP_v}{RT^2} \quad (11)$$

Where

- L = Heat of vaporation in cal. per gm.
 R = Universal gas constant in cal. per gm. mole per deg. K.

Substituting Equations 10 and 11 in Equation 9 we have:

$$q = -\alpha\phi\gamma D \frac{P}{P - P_v} \frac{18LP_v}{RT^2} \frac{dT}{dx} \quad (12)$$

It has been found empirically that when one gas diffuses into another that:

$$D = \text{Constant} \frac{T^n}{P}$$

Where

- T = Absolute temperature
 P = Total pressure
 n = Constant

Krischer (11) has evaluated D for water vapor in air under a thermal gradient and found:

$$D = 4.42 \times 10^{-4} \frac{T^{2.3}}{P} \text{ (cm}^2/\text{sec)} \quad (13)$$

Substituting this value of D (and the value previously given for γ) into Equation 12 gives

$$q = 2.3 \times 10^{-6} \alpha\phi \frac{LP_v}{R(P - P_v)^{0.7}} \frac{dT}{dx} \quad (14)$$

If the temperature gradient at a point can be approximated and if the temperature of that point is known, Equation 14 should make possible the computation of the amount of moisture moving under a thermal gradient due to a molecular diffusion process.

DESCRIPTION OF EQUIPMENT

The equipment used in this experiment is shown in Figure 4, and a schematic representation of the apparatus is illustrated in Figure 5. The plexiglass soil tube was 10 cm. long and 5 cm. inside diameter with a 1/4-inch wall. At both ends the outside diameter is reduced by 1/4 inch for a distance of approximately 1 1/4 inches from the ends of the tube. Two plexiglass end pieces, each with a porous ceramic disc sealed into it, telescope on to the soil tube in such a manner that the porous disc fits snugly against the soil at the end of

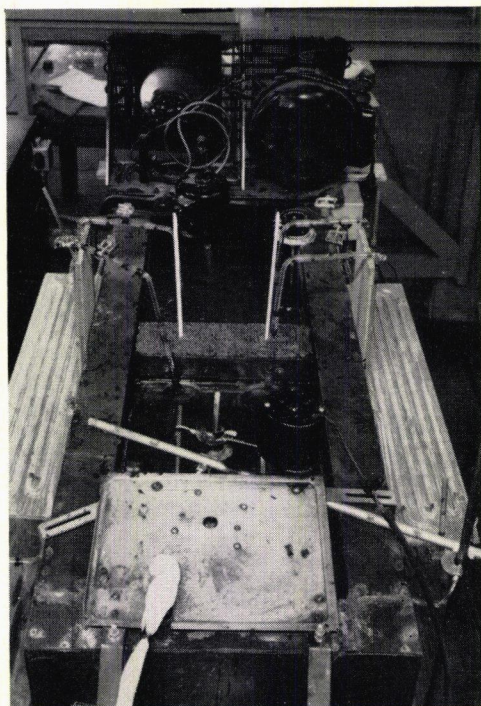


Figure 4. Top view of apparatus.

the tube. Wide rubber bands are placed over the joint formed by the cap and tube to prevent evaporation and to aid in holding the two units together. In construction of the apparatus porous discs were ground to a diameter of 5 cm. so that they had the same diameter as the plexiglass tube. They were then coated with Duco cement and fitted into the end of a piece of tubing 5 cm. in diameter so that about $\frac{1}{8}$ inch of the disc projected above the tube. Another section of tubing about $1\frac{1}{4}$ inches long and $2\frac{1}{4}$ inches inside diameter was then cemented to the tube containing the porous disc. This construction provided a recess $\frac{1}{8}$ inch deep and $\frac{1}{8}$ inch wide around the disc. This space was filled with Glyptal to provide a vacuum-tight seal.

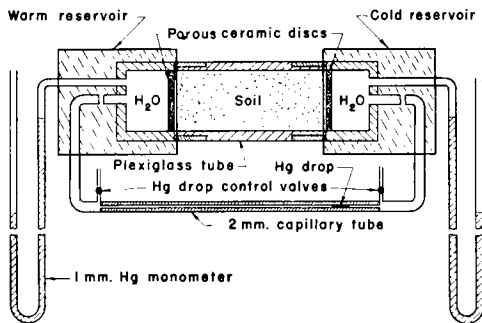


Figure 5. Schematic diagram of apparatus.

Two outlets were provided in each end cap. One outlet was connected to a mercury manometer and the other outlet was attached to a tube which connected the two caps. This connecting tube was in three sections. From each end-piece, an 8-mm. glass tube projected horizontally through the walls of the constant temperature box. These tubes were joined together with a capillary tube of approximately 2 mm. inside diameter. Plastic tubing was used for all connections, and the junctions were coated with Glyptal to form a seal. To provide enough capillary tubing for uninterrupted flow for an extended period, a folded capillary tube was used. Standard 4-foot lengths of capillary tubing were sealed together and then folded at 60-cm. intervals to give an overall tube length of between 3 and 4 meters. This allowed a period of about 3 days to carry out the experiments for the maximum rate of flow encountered. This capillary tube metering system was placed

in the same horizontal plane as the soil tubes so there would be no convection effects.

The mercury manometers served to indicate when an equilibrium condition was attained between the water inside the soil tube and that in the end caps and what magnitude of the soil moisture tension existed for a particular moisture content. They also served to indicate when a steady state process had been reached in the system.

The temperature-control tank consisted of two water baths separated by two partitions. The partitions were 10 centimeters apart and were in the center of the tank. A $\frac{1}{2}$ -hp. refrigeration unit attached to a copper coil served as the temperature control in the cold unit. On the high-temperature side, when temperatures higher than room temperature were desirable, a 750-watt heater operated by a thermostat and relay served to maintain the temperature. When temperatures lower than room temperature were required, a small household refrigeration unit was used to cool the water. This refrigeration unit was allowed to run continuously, and the desired temperature was obtained with the heater-thermostat system. Motor stirrers were placed in both sides to provide a uniform temperature. The thermostat on the hot side was sensitive to within 0.1 C., and the temperature on the low side was maintained within 0.5 deg. of the desired value.

The center partitions were made of brass fastened together with brass bolts. These joined partitions consisted of a lower section soldered to the walls of the bath and a detachable upper section. Each section had two semicircular openings into which two soil tubes could be inserted. When properly equipped with rubber gaskets the upper section bolted to the lower section provided an air space between the two temperature boundaries. A piece of cork 1 inch thick was placed at the top of the upper section to provide a dead air space surrounding the tube.

In a number of experiments moisture distributions in noncirculating systems were compared with distributions where moisture was allowed to circulate as in the equipment described above. For such closed systems, a soil tube exactly like the soil tubes described above were used. A plexiglass cap that fit flush with soil was provided for each end.

METHODS AND PROCEDURES

The characteristics of the soils used in this experiment are shown in Table 1. The soil used was a member of the Hamburg series and was taken from a depth of from 2 to 3 feet in a loess deposit in western Iowa. The fine sand used was taken from a bar on the flood plain of the Missouri River in western Iowa.

A moisture content of approximately 20 percent was used for all experiments carried out with the soil, and a moisture content of about 5 percent was used with the sand. The soil was brought to the desired moisture content by mixing the loess and the prescribed amount of water in a heavy duty mixer similar to, but slightly larger than, mixers found in the ordinary household kitchen. After mixing, the soil was passed through a 2-mm. screen and then placed in air-tight containers and allowed to stand for several days. Differences in moisture contents throughout individual samples were found to be negligibly small.

Two different procedures were used for placing the soil in the tubes at different densities. One procedure was to place the soil in the soil tube in layers and to compact each layer with a given number of blows with a 5-lb. hammer dropped from a height of 3 inches. The hammer used had a diameter just slightly smaller than the internal diameter of the soil tube. Three densities were obtained from this procedure corresponding to one blow per layer, three blows per layer, and ten blows per layer, respectively. Tests indicated approximately a 3-percent variation in densities throughout the tube length. A less-dense specimen was obtained by vibrating the soil and tube with a small vibrator made from a small commercial vibratory saw. The density obtained corresponded to the maximum vibration intensity of the vibrator for a period of 5 seconds.

In the actual operation of an experiment, two samples were prepared at approximately the same moisture content and were compacted under the same compactive effort in the soil tubes. One of the tubes placed in the apparatus permitted the circulation of moisture, and the other tube capped at each end allowed no circulation. The two tubes were placed in the temperature control apparatus so that they were under the influence of the

TABLE 1
SOIL CHARACTERISTICS

Soil Series	Classification		Atterburg Limits			Centrifuge Moisture Equivalent	Carbonates
	Textural	PRA	P.L.	L.L.	P.I.		
Hamburg (55.1) (Loess)	Silty Loam	A-4(8)	27.3	29.6	2.3	11.34	11.00
Mechanical Analysis		Cation Exchange Capacity			pH	Organic Matter (%)	
Particle Size		%					
# 10		0.5		11.2 M.E./100g		8.35	0.24
# 10-40		0.2					
40-270		3.3					
270-5 μ		82.6					
5 μ		13.4					
1 μ		11.4					

same temperature gradient for the same length of time. Rates of flow were observed in the capillary tube metering system throughout the experiment. Durations of experiments varied from 60 to 100 hours.

At the beginning of an experiment the end pieces, metering system, and manometer leads were carefully filled with hot, boiled water and considerable care was taken to make sure that the system contained no air bubbles. A small hydrostatic pressure was applied to the apparatus through opened Clamp 1, Figure 4, for a short period of time to free air from the porous plates. Clamp 1 was then closed. A drop of mercury for tracing the flow was placed in the metering system at the cold end through Valve 1, Figure 4. Valve 1 was then closed and the system was ready for the soil tube. To make good contact between the porous plates and the soil, each plate was coated with a thin layer of wet soil. The end pieces were then telescoped over the soil tube, and the heavy rubber bands were slipped into place. This unit was next placed in the semicircular space in the lower partition assembly, and alongside it, as shown in Figure 4, was placed the tube in which circulation of moisture was prevented. The upper partition assembly was then placed over the tubes and fastened securely to the bottom partition assembly by six screw clamps. The unit was allowed to stand until the mercury manometers reached their equilibrium value. Next, the temperatures at the ends of the soil tubes were applied gradually for 3 to 4 hours until the desired gradient had been

established. Thermometers were placed in contact with the soil in the soil tube through a small opening at the center of each tube. Reading of the movement of the drop of mercury in the metering system was begun when the temperatures in the thermometer reached a steady value. Readings of the drop were continued until constant values were obtained.

At the completion of an experiment the soil tubes were detached from the apparatus and samples of soil of approximately 12 gm. were obtained quickly at points 2 cm. apart along the tube. Moisture determinations were then completed according to standard procedures. Dry densities and the percent of the total volume occupied by air for each sample were determined for all specimens in the usual manner.

A second series of tests was run in which the rates of flow were observed for duplicate samples. The samples were compacted under the same compactive effort and moisture content and then were placed in the apparatus as described above. Both samples were submitted to a temperature gradient of 40 C. to 2 C. and allowed to run until constant rates were attained. Rates of flow were observed on these same samples for gradients in the range of 30 to 1, 20 to 1, and 10 to 0

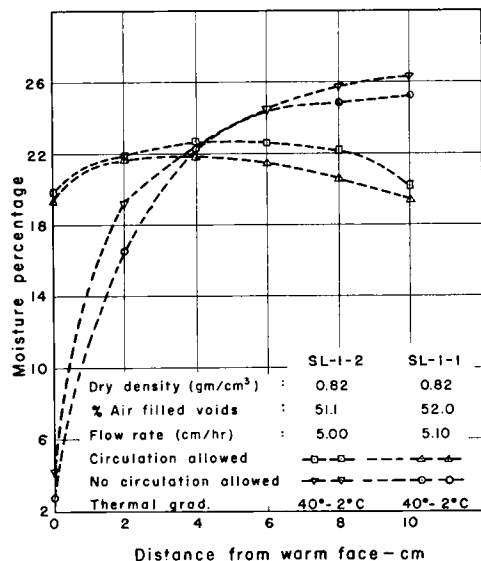


Figure 6. Comparison of moisture distribution for circulating and noncirculating systems.

deg. Thermometers were inserted into the soil at the midpoint to permit observation of the temperature at that point. Duplicate tests for the thermal gradients indicated above were run for effective porosities varying from approximately 8 percent to 50 percent.

SOME EXPERIMENTAL RESULTS

In presenting the results of some experiments utilizing the apparatus described, it should first be pointed out that there was never any tendency in any experiment performed for the drop of mercury in the external capillary tube to move from the warm side to the cold side under the thermal gradient, as one might expect if movement in the liquid phase predominated. This held true not only for experiments using silt loam but also for the preliminary experiments using a loess with approximately 40 percent of less than 5μ clay.

Some typical results of moisture distribution in circulating and noncirculating systems are shown in Figures 6 to 10. Figures 6, 7, 8, and 9 show moisture distributions for a silt loam over a wide range of dry densities for a relatively constant moisture content. Figure 10 is for a fine sand. As indicated earlier each individual experiment included two systems. The one system was an enclosed tube in which moisture accumulated in the cold portions. The other system allowed moisture to return

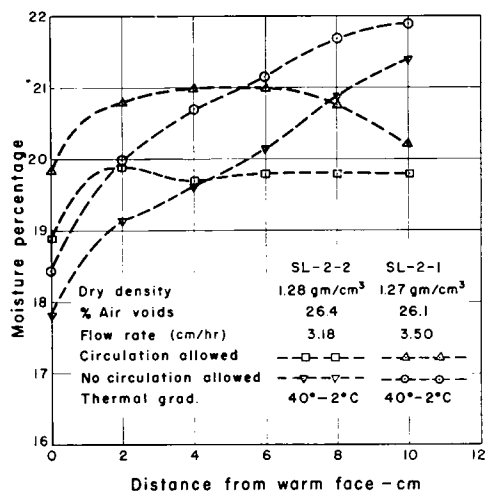


Figure 7. Comparison of moisture distribution for circulating and noncirculating systems.

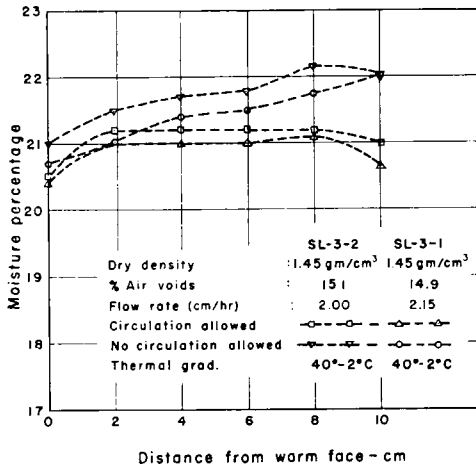


Figure 8. Comparison of moisture distribution for circulating and noncirculating systems.

from the cold to the warm end through an external capillary tube. Results of duplicate experiments are shown in Figures 6 to 8 and for just one experiment in Figures 9 and 10. Dry densities, percent air voids, and rates of flow are indicated in each figure. Rates of flow shown here are linear flow rates in a capillary tube, approximately 2 mm. in diameter. An examination of these figures shows that in all cases moisture accumulated in the colder portion of the tube for the noncirculating systems. The moisture distribution in the circulating systems is seen to be relatively uniform throughout the length of the tube.

It appears from experiments carried out thus far that the rates of flow in the circulating system can be maintained indefinitely provided the thermal gradient is maintained. But the length of time for any experiment has not exceeded 10 days. There is no indication in data collected to date that the flow rate decreases rapidly with time as is characteristic for flow in saturated soils. Clogging of pores with biological secretions is believed to be the principal reason for reduction of the permeability in the latter case. However, if the movement of moisture is a molecular diffusion process, considerable reduction in flow rate would not be expected to the same extent as in saturated flow.

Although the moisture distribution curve for the circulating system is relatively uniform in comparison with the other system, there

is a characteristic lowering of the moisture content on each end of this curve. This may be explained by the following:

When the temperature difference is first applied, the rate at which moisture moves out of the soil adjacent to the porous plate at the warm side exceeds the rate at which moisture is accumulating in the soil adjacent to the cold porous plate. Eventually a steady state of flow is reached, and the amount leaving the vicinity of the warm plate equals that reaching the cold plate. Any further tendency for reduction of moisture content ceases at this point. This explanation is substantiated by the fact that as the temperature difference is first applied the mercury columns rise quite quickly for a period of time. After that they appear to oscillate slightly about an equilibrium point.

On the basis of previous reasoning in this discussion, moisture which circulates through the external capillary tube during a steady state should be moisture other than that which moves through the soil continuously in the liquid phase. Therefore, since moisture accumulates in the noncirculating system and does not appreciably accumulate in the circulating system, it seems that moisture movement in the liquid phase is not the predominant mechanism for the soils used here.

The effect of the density on the rate of movement is also observable from the moisture-distribution curves. The increased rate of movement is reflected in the noncirculating

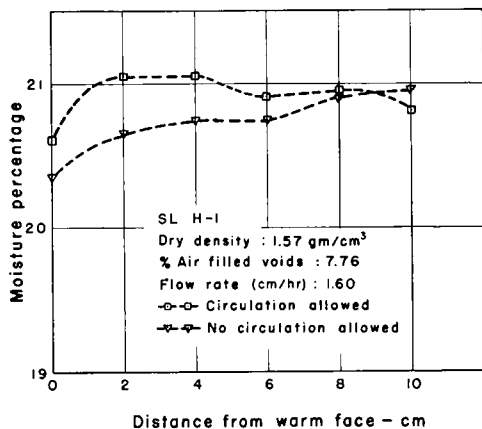


Figure 9. Comparison of moisture distribution for circulating and noncirculating systems.

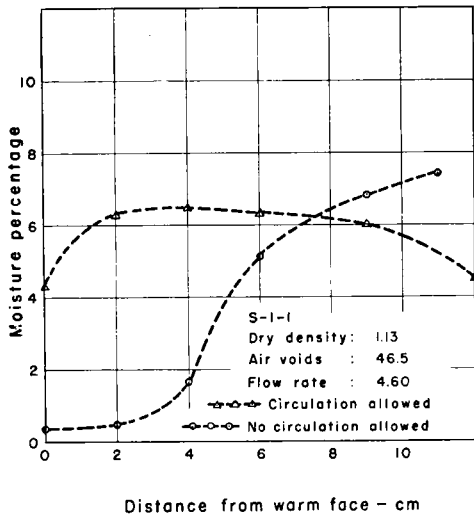


Figure 10. Comparison of moisture distribution for circulating and noncirculating systems.

systems as well as in those in which circulation was allowed. Rates of movement become increasingly lower as the density approaches the standard Proctor density. Figure 9 represents a sample near standard density; as it is more difficult to establish a good contact between the porous ceramic plates and the soil at this density, the value listed seems the least reliable of the four densities considered.

Table 2 indicates the relation between the flow rates and the temperature differences for six different tests. The first four tests have about the same moisture content and dry density. Specimens for Tests 5 and 6 were given the same compactive treatment as those for Tests 1 to 4, but the initial moisture content was reduced. The data tabulated in Table 2 are shown graphically in Figure 11. Curve A shows the relationship between the average flow rate for the first four tests and the temperature of the warm side. Curve B shows the same for the remaining tests. These data serve to point out that the flow rate is not a linear function of the temperature gradient. That is, the flow rate for a thermal difference of ten degrees is greater if the bounding temperatures are in the range of 40 deg. to 30 deg. than if they are 20 to 10 deg. These data also show that the flow rate increases as the percent of air-filled voids are increased.

TABLE 2
RELATIONSHIP BETWEEN FLOW RATE AND THERMAL GRADIENT

Trial No.	Dry Density (Gms/cm ³)	% H ₂ O	% Air Voids	Temp. Diff.	Rate (Gms/hr cm ²) of flow
1	1.32	21.8	21.5	40° - 2°C	4.40 × 10 ⁻³
				30° - 2°C	2.86 × 10 ⁻³
				20° - 1°C	1.47 × 10 ⁻³
				10° - 0°C	0.56 × 10 ⁻³
2	1.33	22.1	20.5	40° - 2°C	4.46 × 10 ⁻³
				30° - 2°C	2.86 × 10 ⁻³
				20° - 1°C	1.43 × 10 ⁻³
				10° - 0°C	0.54 × 10 ⁻³
3	1.32	22.4	20.2	40° - 2°C	4.36 × 10 ⁻³
				30° - 2°C	2.54 × 10 ⁻³
				20° - 1°C	1.32 × 10 ⁻³
				10° - 0°C	0.47 × 10 ⁻³
4	1.33	22.5	19.6	40° - 2°C	4.36 × 10 ⁻³
				30° - 2°C	2.68 × 10 ⁻³
				20° - 1°C	1.43 × 10 ⁻³
				10° - 0°C	0.51 × 10 ⁻³
5	1.26	17.07	30.7	40° - 2°C	5.29 × 10 ⁻³
				30° - 2°C	3.33 × 10 ⁻³
				20° - 1°C	1.73 × 10 ⁻³
				10° - 0°C	0.71 × 10 ⁻³
6	1.26	17.3	30.4	40° - 2°C	5.30 × 10 ⁻³
				30° - 2°C	3.32 × 10 ⁻³
				20° - 1°C	1.79 × 10 ⁻³
				10° - 0°C	0.71 × 10 ⁻³
7	1.22	16.55	33.9	40° - 2°C	5.35 × 10 ⁻³
				30° - 2°C	3.47 × 10 ⁻³
				20° - 1°C	1.67 × 10 ⁻³
				10° - 0°C	0.63 × 10 ⁻³
8	1.23	16.55	33.0	40° - 2°C	5.58 × 10 ⁻³
				30° - 2°C	3.47 × 10 ⁻³
				20° - 1°C	1.64 × 10 ⁻³
				10° - 0°C	

In all tests listed in Table 2, temperatures were recorded at the center of the tube. For Tests 1 to 4 the temperature at the midpoint corresponding to boundary temperatures of 40 to 2 C. was 23.8 C. The temperature gradient is therefore nonlinear. However, since

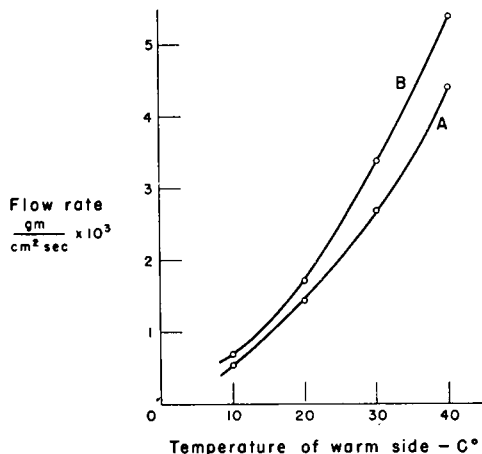


Figure 11. Relationship between flow rate and thermal gradient.

the deviation of the temperature gradient is not very far from linearity, an estimate of the temperature gradient at the midpoint of the tube of $38/10 = 3.8$ C. per cm. should be a fair approximation.

With this approximation of the temperature gradient the amount of the molecular diffusion through a unit cross section per unit time at the center of the tube using Equation 7 may be estimated. Test 1 boundary conditions of 40 to 2 C. and the value of a as given by Penman (15) results in

$$a = .66, \quad \phi = .215; \quad T = 23.8^{\circ}\text{C};$$

$$\frac{dT}{dx} = 3.8^{\circ}\text{C}/\text{cm}$$

$$L = 583.7 \text{ cal/gm}; \quad P_v = 22.11 \text{ mm of Hg};$$

$$P = 760 \text{ mm Hg}$$

Substituting these values in Equation 14

$$q = 2.3 \times 10^{-6} \alpha \phi \frac{LP_v}{(P - P_v)T^{0.7}R} \frac{dT}{dx} \quad (\text{gm}/\text{sec cm}^2)$$

therefore

$$q = 2.03 \times 10^{-7} \text{ (gm. per sec.) per sq. cm.}$$

The cross-sectional area of the soil tube was 19.6 sq. cm.; therefore the total calculated flow is

$$q = 19.6 \times 2.03 \times 10^{-7} = .397 \times 10^{-5} \text{ (gm. per sec.)}$$

The measure value for this case was 2.4×10^{-5} (gm. per sec.)

Thus the measured rate of flow is over six times the value estimated, assuming a molecular diffusion process and using values of α and D as found in the references. A comparison of calculated values and other measured values listed in Table 2 give results comparable to the example given above. Perhaps either the values of α and D used in estimating q are not correct or that some other mechanism, such as that proposed by Smith (18), is operative in causing thermal translocation of moisture. However these data are insufficient to draw any definite conclusions as to the reason for differences between measured and estimated values.

CONCLUSIONS

An apparatus for measuring the rate of thermal migration of soil moisture in a steady state process has been described. Experimental results show that the rates of flow are greatly influenced by the density and percent of air-filled voids. The results of comparisons of the moisture distributions in circulating and noncirculating systems, combined with the fact that the drop of mercury in the external capillary tube never moves from the warm to the cold side, tend to substantiate the belief that the predominant method of movement of soil moisture is not in the liquid state for moisture contents used in these experiments.

A comparison of calculated flow rates for molecular diffusion with observed values indicates that the measured values are approximately six times the computed values. This would seem to indicate that either the values of α and D taken from the cited references are not accurate for this system or that some mechanism other than molecular diffusion is operative in the process.

The rate of flow was found to be a non-linear function of the temperature gradient for a given dry density and moisture content. Flow rates for temperature differences in the range of 40 C. to 30 C. were greater than for 10 C. to 0 C.

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