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Movement of soil moisture under a thermal gradient

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NOTE TO USERS

MOVEMENT OF SOIL MOISTURE UNDER

A THERMAL GRADIENT

by

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A Dissertation Submitted to the

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TABLE OF CONTENTS

I. INTRODUCTION

In the field of soil engineering the ability of a highway or air strip to withstand loading is a sensitive function of the moisture content of the soil. Consequently, the general subjects of moisture movement in soil, moisture accumulation under impervious pavements, and subgrade moisture control are of prime importance. In the field of agriculture, storage and loss of soil moisture, resulting from various methods of soil moisture movement, are of great importance in their relation to plant growth.

A number of investigators have shown that moisture movement in soil occurs on the application of a thermal gradient. Heat flows continually outward from the earth's surface, and as temperature conditions on the earth's surface fluctuate continuously, thermal gradients of varying amount and direction exist within the earth's crust. A review of the literature shows that there is considerable disagreement, not only as to the nature of the mechanism responsible for this movement, but also as to the amount and relative importance of such a movement.

Previous investigation by other workers, pertaining to soil moisture movements under thermal gradient has been more or less of a qualitative nature. Briefly, such experiments have involved the application of a temperature difference to opposite sides of

soil mass with the subsequent observation of moisture accumula-tion at the warm side. Most of the experiments have been in systems in which the total amount of moisture remained constant.

In the present study an attempt has been made to develop an apparatus for making a quantitative measurement of that portion of the moisture moving in the gaseous state. An attempt is also made to determine the relative importance of movement in the liquid state versus movement in the vapor state. Data showing the relationship of flow rate and temperature difference, and flow rate and percent of air-filled voids are presented.

II. REVIEW OF LITERATURE

In 1892 King (11) experimented with fluctuations of ground water in a large, cylindrical, galvanized iron tank, six feet high and thirty inches in diameter. He observed that the water level in a circular well in the middle of the tank rose daily and fell again at night. The application of cold water to the outside of the cylinder by means of a hose caused the water in the well to fall. He says:

> The water was applied on a hot, sunny day just after dinner, when the water was rising in the well, and the result was an immediate change in the curve, the water beginning to fall in the well and turn the pen up. The water was then turned off, and the result of this change was to stop the fall of the water in the well, as shown by a change in the direction of the curve downward again. After the lapse of about another hour the water was again turned on, with the result that was first obtained, and again when the water was withdrawn the curve was once more reversed. (11, p. 60)

He further states:

> These experiments show that there was a positive connection between changes in soil temperature and changes in the movement of water in the soil. Since the water left the well and entered the soil with a lowering of temperature, it follows that the observed changes could not be the result of a change in the volume of the cylinder due to shrinkage and expansion, for movements of the water were in the opposite direction from what a change in volume would have produced. (11, p. 61)

Some other early 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 differ-
ent but uniform moisture content in opposite halves of brass
tubes eight inches long and one and one-half inches in diam-
eter and then to close both ends with a rubber stopper. The
more moist half of the soil tube was kept at a high temper-
ature and the less moist half was kept at a lower temperature
for a certain length of time, after which the moisture per-
centages 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° to 20° C. and 0° to 40° C.

He observed that moisture moved from the warm soil to
the cold soil at both temperature ranges and that the 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 eight
inch brass tube by an "air ring". The air ring or disk, was
one-quarter 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° to 0° C. and 20° to 0° C. for a period of eight 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.

Movement of moisture in soil under a thermal gradient was reported by Lebedeff (13) in Russia in 1927. 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% 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 square 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.

Smith (19) was interested in determining the heat conduc-
tivity 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 (20) 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 move-
ment 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.
He says:

> 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 con-
> denses, to some degree, on the capillary bodies immedi-
> ately 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. (20, p. 522)

Maclean and Gwatkin (15) studied the movement of soil
moisture under a thermal gradient and concluded that the mech-
anism 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.

For isothermal conditions, Linford (14) points out, that in
a soil column above a free water surface, mechanical equilibrium
of liquid films and equilibrium of the films with its vapor must
occur simultaneously. He calculated the diffusion rate which
would occur due to a vapor pressure gradient existing between
a free water surface and a curved surface of .01 cm. radius.
Applying this diffusion rate to soils placed in a closed vessel
containing water, he showed that considerable time would be
required to get a measurable amount of water distilled into the
soil. He says:

> In order to prove that an equilibrium state drier
> than complete saturation exists, one must recognize

and take account of the following conditions: In
order to fill the air pockets in the soil one must be
prepared to allow the experiment to run over a period
of many years, that is, 100 years for each gram of
water transferred, after the pores are 0.01 cm. in
radius. (14, p. 232)

Trejo (21) 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, enclosed in a Lucite

cylinder was placed between a steam chamber and a frigid

chamber. Moisture movements for rapid and gradual applica-

tions of the thermal gradients were determined in natural

New Jersey Hagerston soil. He found that the moisture dis-

tribution throughout the soil tube after application of the

thermal gradient depended upon the rate of application.

Gradual application of the gradient caused a linear distri-

bution of moisture throughout the sample with increasing

moisture percentages toward the cold end. Rapid applica-

tion of the gradient gave an "S" shape moisture distribution

curve and sudden application gave a parabolic distribution

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 (23) 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 temperatures.

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 No. 4 above as most important and developed a theory analogous to electro-osmosis 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 Gwatkin. He concluded that the two coefficients compared favorably. With respect to the movement of moisture in the film phase Winterkorn states as follows:

> 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. (23, p. 454)

Gouda and Winterkorn (8) carried out experiments on move-
ment of moisture under a temperature gradient with the aim of
investigating similarity between electro-osmosis and "thermo-
osmosis". The soil was placed in Lucite cylinders 10 cm.
long and 5 cm. in diameter. A temperature gradient was estab-
lished 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° C/cm., thus most of
the water is moved in the initial stages when the equilibrium
is disturbed, and only very slight movement occurs during the
latter and more extended period.

4. The voltages developed at the beginning of the experi-
ment are very close to or only slightly lower than the maximum.

Croney and Coleman (3) have discussed the movement of soil
moisture in road foundations. Using an equation developed by

Kelvin, the following equation relating soil vapor pressure to temperature was developed.

$$\frac{T_1}{T_2} = \left(\frac{\rho_1}{\rho_2}\right)\left(\frac{\theta_1}{\theta_2}\right) \frac{Log_{10} \frac{H_1}{100}}{Log_{10} \frac{H_2}{100}}$$

Where θ_1 = Temperature in first state

θ_2 = Temperature in second state

ρ_1 = Density of water in the first state

ρ_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 as follows:

> 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 labora-
> tory 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. (3, p. 172)

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 one-third of the moisture equivalent.

Edlefsen and Smith (7) point out that the vapor pressure of soil moisture corresponding to approximately 15 atmospheres 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 Rohnalter (12) measured the diffusion coef-
ficient for water in air under a thermal gradient. They give
the following value for the diffusion coefficient:

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

Where $P_o =$ Total pressure in Kilograms/meter^2

$T =$ Absolute temperature

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

$$G_d = - \frac{K}{\mu \, R_d T} \frac{P_o}{P_o - P_s} \frac{dP_s}{dx}$$

Where $G_d =$ Amount of vapor movement (kg/meters 2/hr)

$K =$ Diffusion coefficient of water in air (meters^2/hr)

$\mu =$ A dimensionless factor

$R_d =$ Gas constant for water vapor (meters.kg/kg.^{o}k)

$P_o =$ Total pressure (kg/meters^2)

$P_s =$ Partial water vapor pressure (kg/meters^2)

Penman (17) 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/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_o = .66S. Where:

  D = Diffusion coefficient in porous materials

  D_o = Diffusion coefficient in air only

  S = Volume fraction of air filled voids

Van Bavel (22) in a recent study aimed at evaluating the relationship between porosity and the diffusion constant for gases in soil, considers Penman's results as the best yet

obtained; however, in his criticism of Penman's procedures, he says,

> The method used by Penman is never-the-less open to three criticisms. The first pertains to the evaluation of the grid effect already discussed. The second -- recognized in Penman's paper -- concerns the variability of the diffusion constant due to different vapor-air ratios at different temperatures and at different points in the diffusion column. Furthermore, there is some uncertainty in the exact determination of the surface temperature of the evaporating liquid. The third objection is a matter of the applicable theory, as explained in the following. Closure of the container on one side causes a current of air-vapor mixture to flow in the same direction as that of the vapor diffusion. This causes the partial pressure gradient to vary exponentially rather than linearly, an effect that may not be neglected without serious error. (22, pp. 93,94)

Van Bavel designed apparatus and developed appropriate formulas which he considered were free from the above stated criticisms. From the results of his analysis he concludes that the relation $D = 0.60 D_o$ best represents the relationship between a diffusion constant of a gas in soil and the diffusion constant of a gas in air.

DeVries (5) computed theoretically the ratio of $D/D_o = a$, 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:

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

Where q = Vapor flux in gm./cm^2Sec

  α = Dimensionless factor depending on the structure

  ϕ = Volume fraction of air filled pores

  D = Diffusion coefficient of water in air cm^2/sec

  γ_w = $\dfrac{0.289 \times 10^{-3}}{T}$ = mass of 1 cm^3 water vapor at

    1 mm. pressure and temperature in gm/cm^3mmHg

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

  P_v = Partial pressure of water vapor in mm. Hg

Penman and Schofield (18), assuming that there existed the unique dependence $D/D_o = 0.66S$, estimated the extent of water movement in soils by molecular diffusion under a thermal gradient. They concluded that even under gradients more extreme than any thing likely to arise in nature the transfer was very small and that distillation under a temperature gradient was a negligible factor in soil water movements.

III. THEORETICAL ANALYSIS

A. Introduction

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.

B. Capillary System

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 capillary model represents the air-filled soil pores in the unsaturated soil system.

Position No. 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 No. 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.

P = Pressure drop across air-water interface.

T = Surface tension of the liquid.

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

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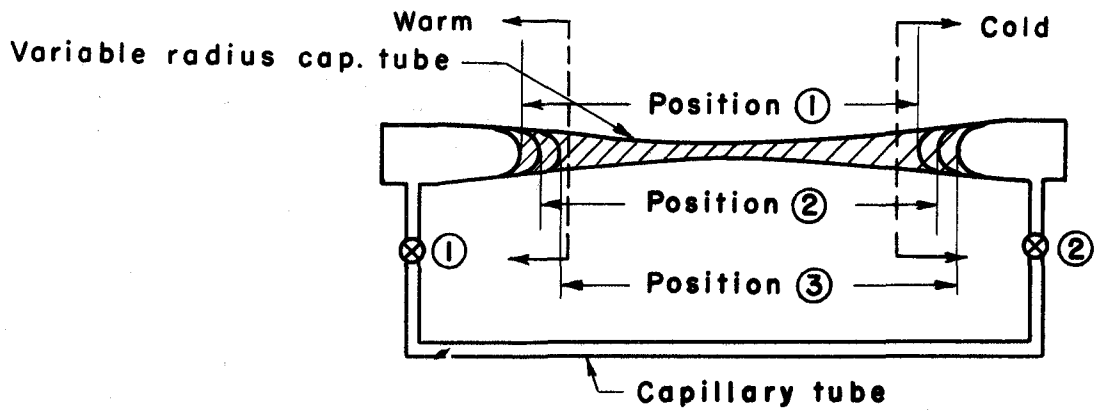
$$\Delta P = \frac{2T}{r}$$

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

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

Fig. I. Capillary model
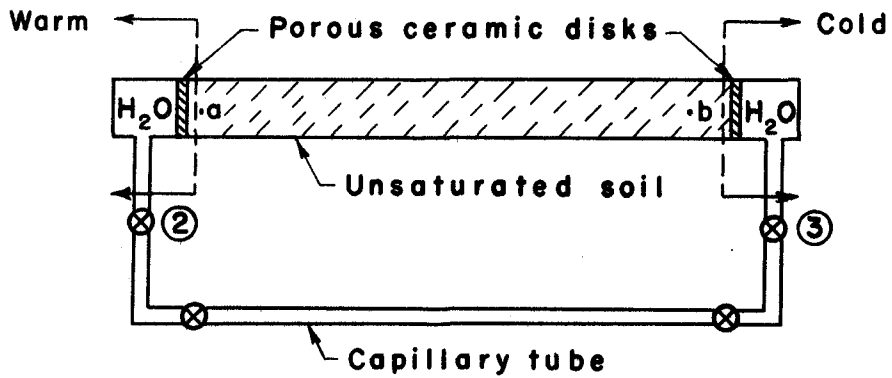
Fig. 2. Soil system.

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 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:

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

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 No. 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 as follows:

(1) That increase having to do with the effect of temperature on surface tension.

(2) That increase resulting from vapor flow.

C. Soil System

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 point _a_ to point _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 point _a_ toward point _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 points 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 to 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.

D. Principles Underlying Development of Apparatus

The analogy between the capillary model and the unsaturated soil needs some modification, however, at this point. The movement of capillary moisture is a very slow process at moisture contents other than those near saturation. Investigators (16) have shown that the capillary conductivity is essentially zero at the field capacity (the amount of water held in the soil after the excess gravitational 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 No. 2 and No. 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. [1] 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.

E. Hypothesis for Distinguishing between Liquid and Vapor Flow

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

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[1] Assumption verified by laboratory experiment.

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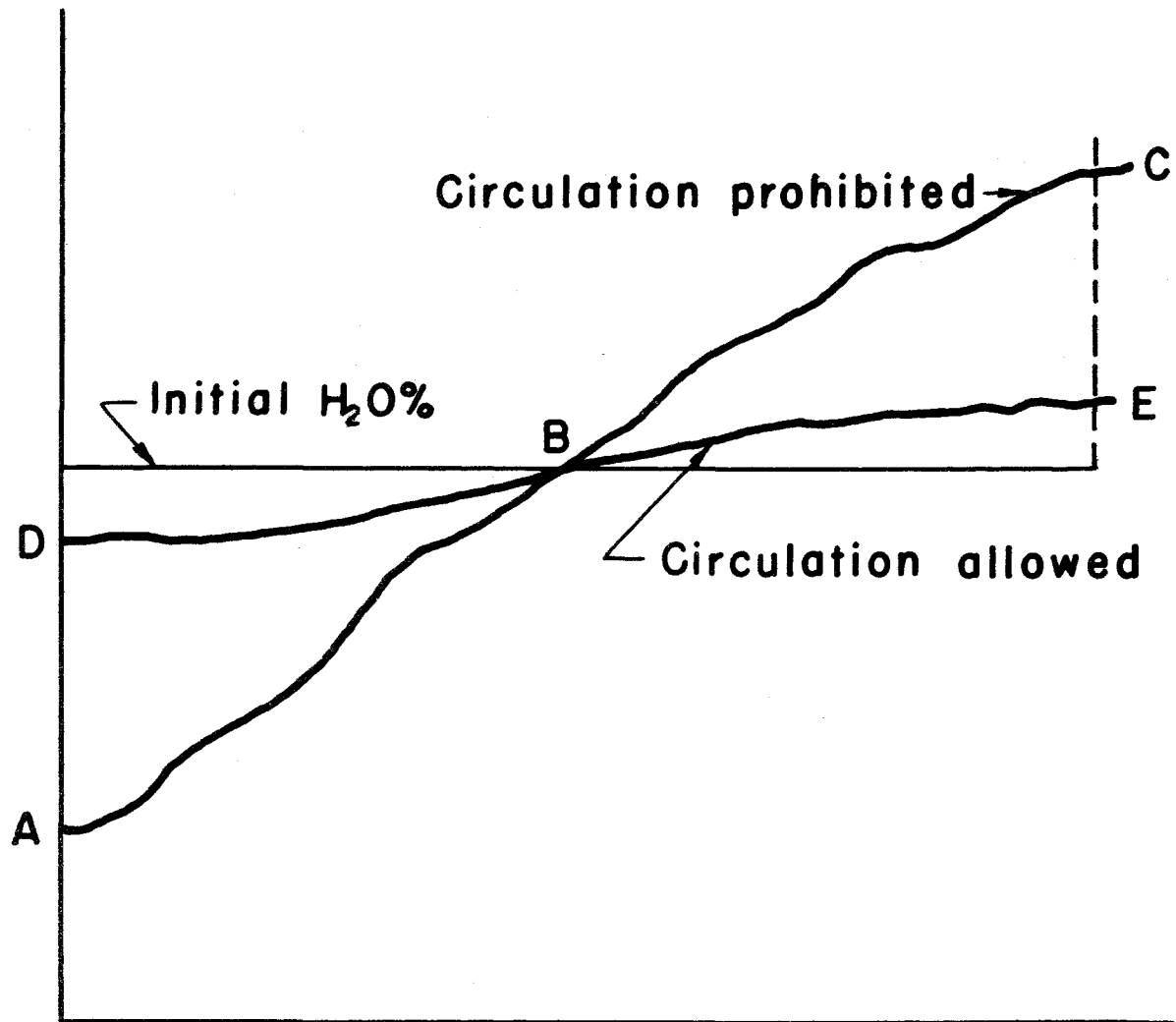
Fig. 3. Hypothetical distribution of moisture moving in liquid and vapor phases.

Circulation prohibited

Initial H$_2$O%

Circulation allowed

Moisture %

Distance from warm face

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, it can be concluded 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, it may be concluded that the movement of soil moisture was
equally divided between liquid and vapor phases. In general
it can be stated 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 pre-
dominant mechanism of movement is associated with vapor movement.

F. Development of Flow Equation

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

$$q = -\frac{Ddc}{dx} \qquad (1)$$

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

D = Diffusion coefficient

$\dfrac{dc}{dx}$ = Concentration gradient of the substance (Rate

of change of mass per unit volume with x)

Now equation (1) can be written as:

$$q = -D \frac{dc}{dP} \frac{dP}{dx} \qquad (2)$$

If it is assumed that water vapor obeys the perfect gas law with P_v = vapor pressure in mm. Hg; V = volume in cm^3; m = mass in gms; M = molecular weight in gms; R the universal gas constant in $\dfrac{mm. \; Hg \; cm^3}{Gm \; mole \; Deg \; K}$; and T the absolute temperature, then $P_v = \dfrac{c}{M} RT$ and $\dfrac{dc}{dP_v} = \dfrac{M}{RT}$. Substituting this expression in equation (2) gives:

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

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

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

A similar equation can be written for the air movement

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

The net flow of air must be zero so that equation (5) yields

$$u = \frac{D}{P_a}\ \frac{dP_a}{dX} \tag{6}$$

Now $P_a = P - P_v$

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

Therefore $u = -\ \dfrac{D}{P - P_v}\ \dfrac{dP_v}{dX}$ $\tag{7}$

Substituting equation (7) in (4) gives

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

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

Letting $\curlyvee = \dfrac{2.89 \times 10^{-4}}{T}$

we have $q_v = -D\,\curlyvee\,\dfrac{P}{P - P_v}\ \dfrac{dP_v}{dX}$ $\tag{8}$

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 (6). 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:

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

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 (cm^2/sec)

$\Upsilon = \dfrac{0.289 \times 10^{-3}}{T}$ = mass of 1 cm^3 water vapor at

1 mm. pressure and temp. T in gm/cm^3 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:

$$\frac{dP_v}{dT} \quad \frac{dT}{dx} = \frac{dP_v}{dx} \tag{10}$$

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

$$\frac{dP_v}{dT} = \frac{18LP_v}{RT^2} \tag{11}$$

Where L = Heat of vaporation in cal/gm

R = Universal gas constant in cal/gm mole °K

Substituting (10) and (11) in (9) we have:

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

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

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

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

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

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.

IV. DESCRIPTION OF EQUIPMENT

The design of the equipment used in this experiment was based on principles outlined in the previous section. A photograph of the equipment 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 in. wall thickness. At both ends the outside diameter is reduced by 1/4 in. for a distance of approximately 1 1/4 in. 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 smugly against the soil at the end of 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 coated with Duco cement and fitted into the end of a piece of tubing 5 cm. in diameter so that about 1/8 in. of the disc projected above the tube. Another section of tubing about 1 1/4 in. long and 2 1/4 in. inside diameter was then cemented to the tube containing the porous disc. This construction provided a recess 1/8 in. deep and 1/8 in. wide around the disc. This space was filled with Glyptal to provide a vacuum tight seal.
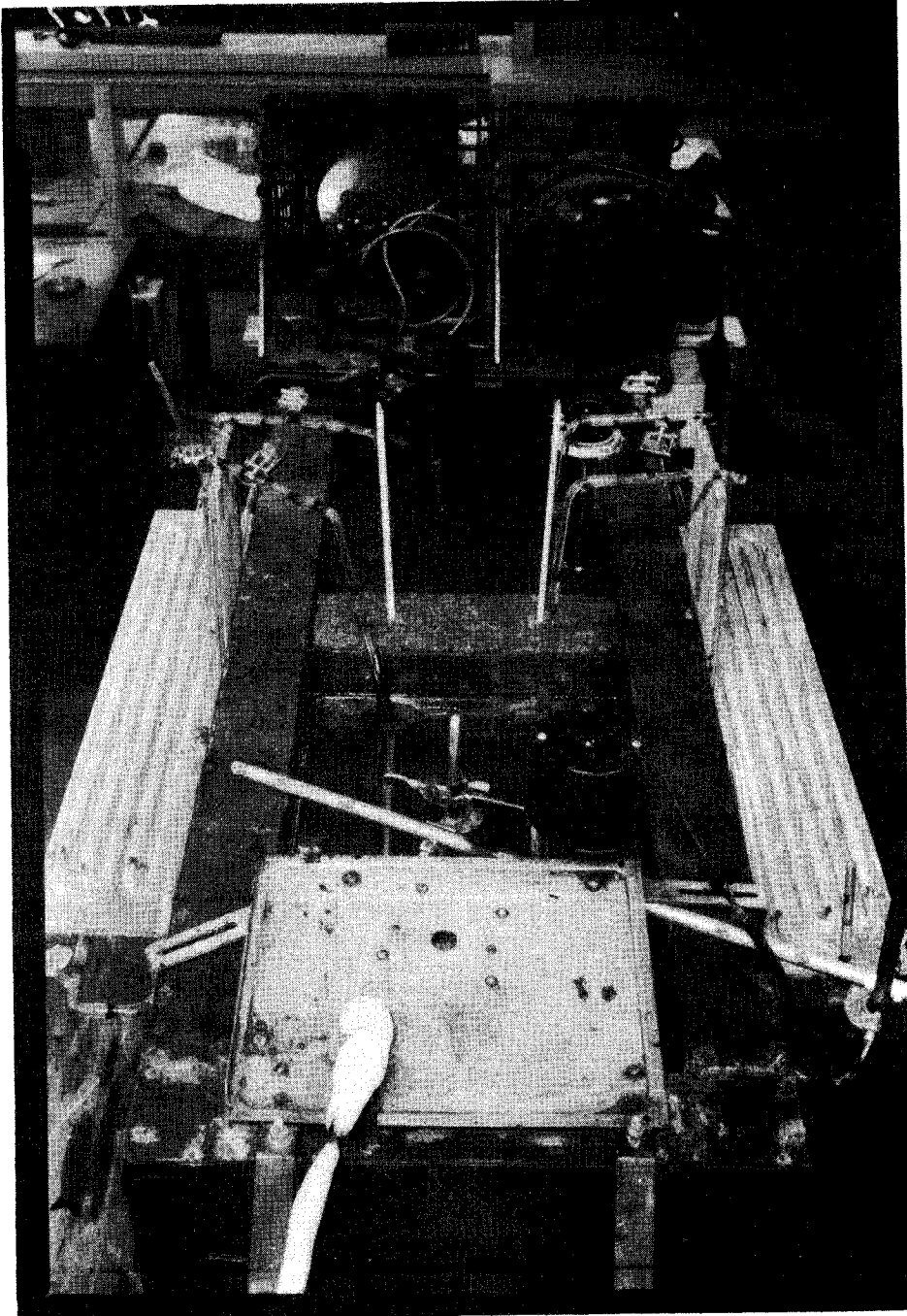
Fig. 4.   Top view of apparatus.

Warm reservoir

Cold reservoir

Porous ceramic discs

H₂O Soil H₂O

Plexiglass tube

Hg drop

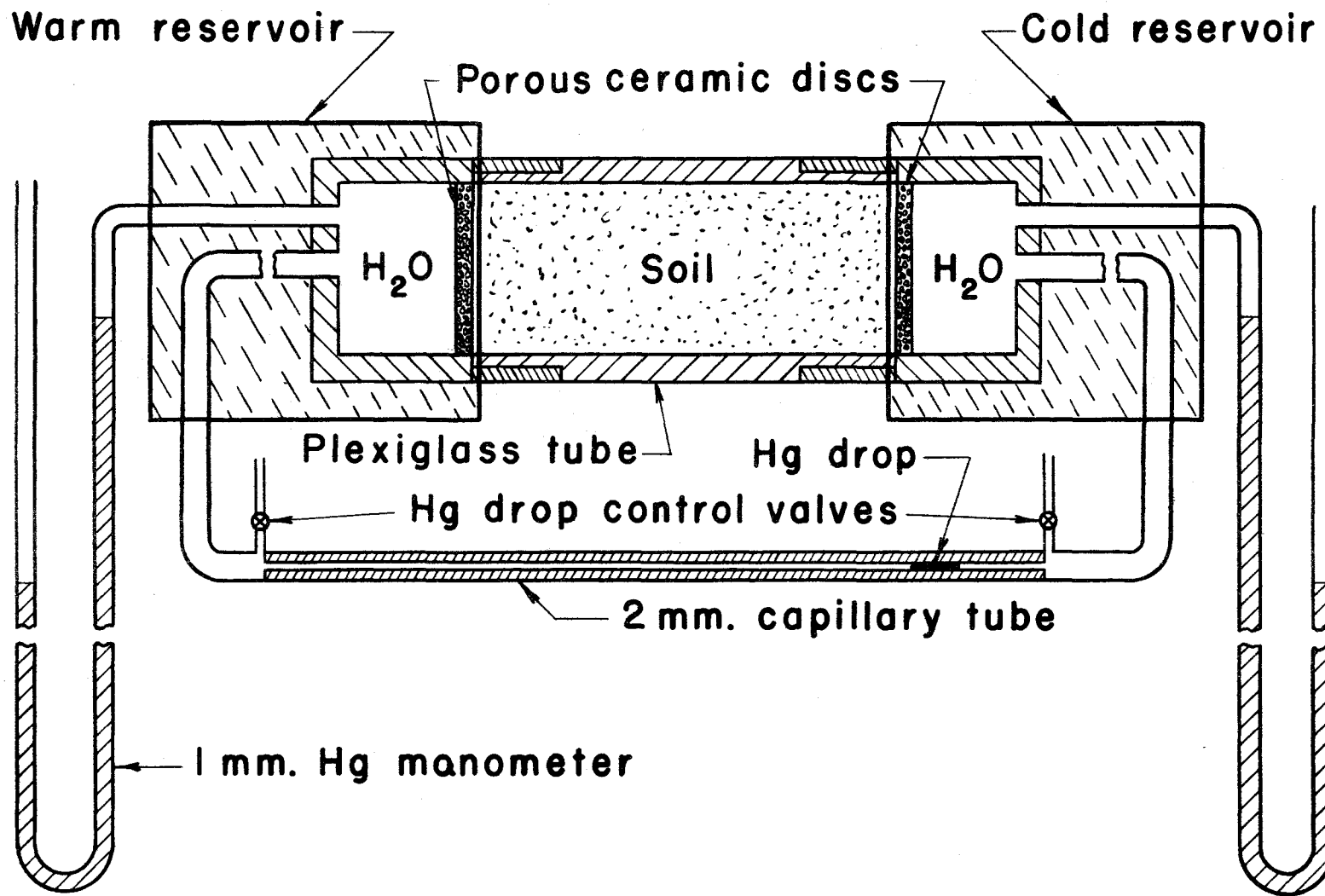Hg drop control valves

2 mm. capillary tube

I mm. Hg manometer

Fig. 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 3 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 four foot lengths of capillary tubing were sealed together and then folded at 60 cm. intervals to give an overall tube length of between three and four meters. This allowed a period of about three 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 ten centimeters apart and were in the center of the tank. A one-fifth horsepower 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 $0.5°$ C. 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 in. 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 a closed system, 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.

V. METHODS AND PROCEDURES

A. Operation of Equipment

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 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 No. 1, Figure 4 for a short period of time to free air from the porous plates. Clamp No. 1 was then closed. A drop of mercury for tracing the flow was placed in the metering

system at the cold end through valve No. 1, Figure 4. Valve No. 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 gms. 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 $40^\circ - 2^\circ$ 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 $30^\circ - 2^\circ$ C., $20^\circ - 1^\circ$ C., $10^\circ - 0^\circ$ C. 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% to 30%.

B. Placement of Soil in Tubes

The soil was placed in the tube in layers and compacted by impact with hammers of different weights. The hammers used

weighed 5 and 2 1/4 pounds respectively and were dropped through
a distance of 3 inches. The state of compaction desired was
obtained by varying either the weight of the hammer or the
number of blows per layer. In general, plus or minus four
layers of soil of equal amount were placed in each tube.
Maximum density occurred in the bottom of the tube, with a
maximum variation of about 3% between top and bottom. One
exception to this compaction procedure was used to obtain
an effective porosity of approximately 50% for one experiment
involving comparison of moisture distributions in circulating
and non-circulating systems. In this instance compaction was
obtained by vibrating the soil 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 five seconds.

C. Properties of Soil Used

The characteristics of the soils used in this experiment
are shown in Table I. The soil used was a member of the Hamburg
series and was taken from a depth of from two to three 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% was used for all experiments carried out with the soil, and about a 5% moisture content 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.

TABLE I. 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			
#10-40	0.2	11.2 M.E./100g	8.35	0.24
40-270	3.3			
270-5μ	82.6			
5 μ	13.4			
1 μ	11.4			

VI. EXPERIMENTAL RESULTS

A. A Comparison of Moisture Distribution in Circulating and Non-circulating Systems

In presenting the results of some experiments utilizing the apparatus herein 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% of less than 5μ clay.

Some typical results of moisture distribution in circulating and non-circulating systems are shown in Figures 6 to 10. Figure 6 shows the moisture distributions for a silt loam in which the percent air filled voids are approximately 50% and the moisture percentage is near 20%. 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 from the cold to the warm end through an external capillary tube. The initial moisture content for both systems

Fig. 6. Comparison of moisture distribution for circulating and noncirculating systems.
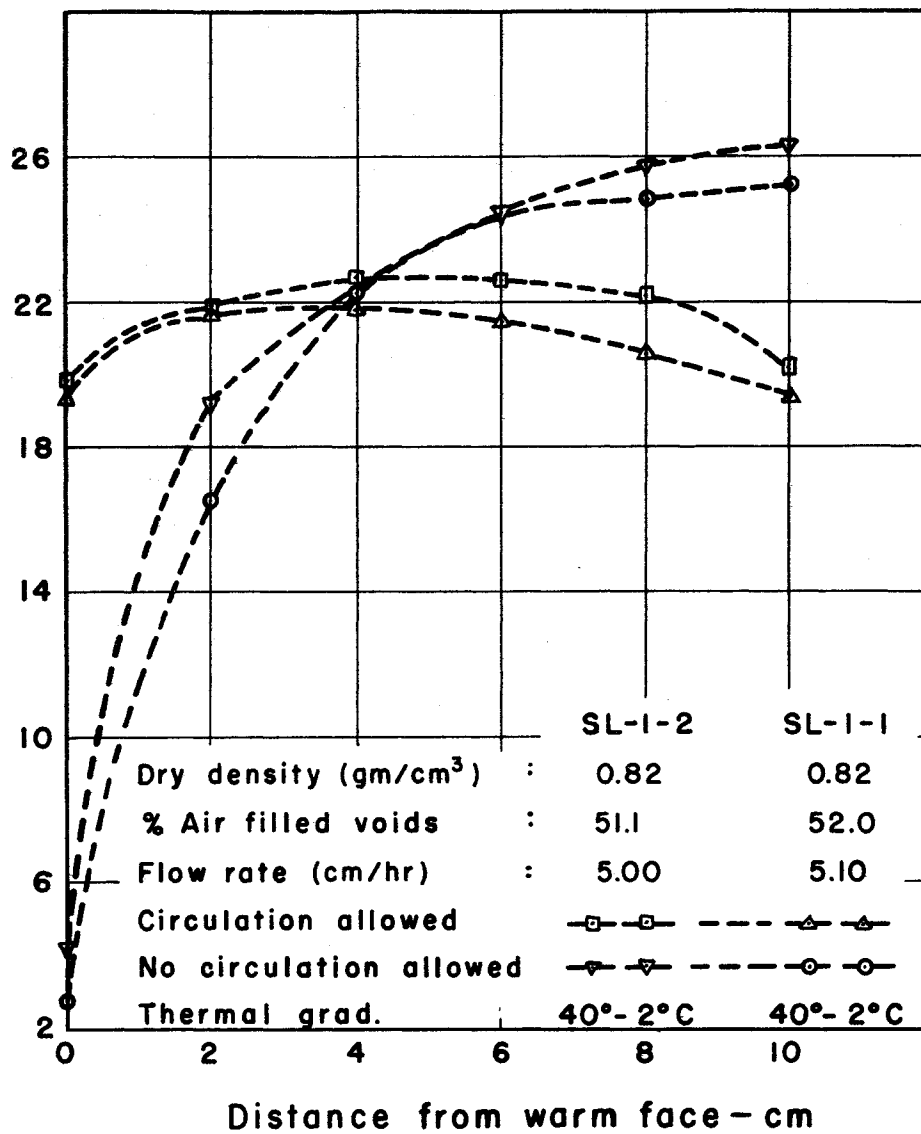
Moisture percentage

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

	SL-2-2	SL-2-1
Dry density	1.28 gm/cm³	1.27 gm/cm³
% Air voids	26.4	26.1
Flow rate (cm/hr)	3.18	3.50
Circulation allowed	— —□— —□— —	— —△— —△— —
No circulation allowed	— —▽— —▽— —	— —⊙— —⊙— —
Thermal grad.	40°–2°C	40°–2°C

Distance from warm face – cm

Moisture
percentage

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

	SL-3-2	SL-3-1
Dry density :	1.45 gm/cm^3	1.45 gm/cm^3
% Air voids :	15.1	14.9
Flow rate (cm/hr) :	2.00	2.15
Circulation allowed		
No circulation allowed		
Thermal grad.	40°-2°C	40°-2°C

Distance from warm face - cm

Moisture percentage

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

		SL-4-1	SL-4-2
Dry density (gm/cm³)	:	1.585	1.545
% Air voids	:	7.9	7.5
Flow rate (cm/hr)	:	0.83	0.78
Circulation allowed	:	-◻--◻--◻--	--△--△--△-
No circulation allowed	:	-▽--▽--▽--	--◉--◉--◉-
Thermal grad.	:	40°-2°C	40°-2°C

Distance from warm face
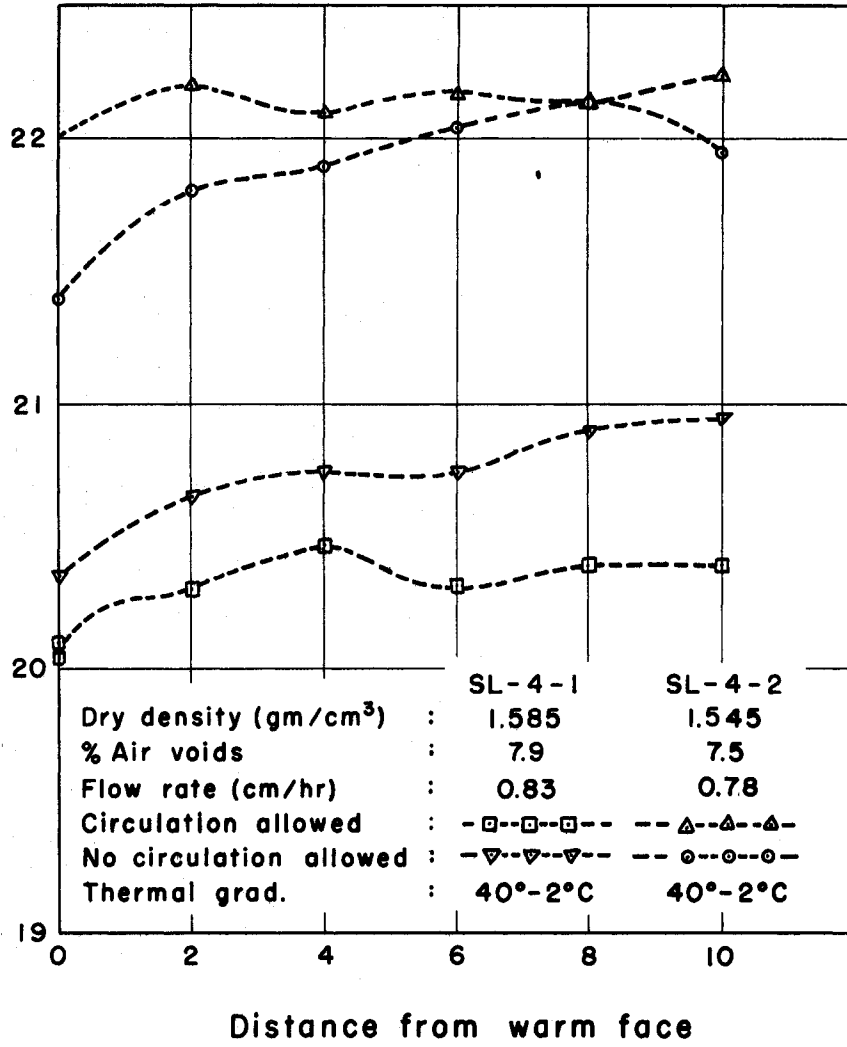
Moisture
percentage

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

S-l-l
Dry density: 1.13
Air voids   :   46.5
Flow rate   :   4.60
△△△ Circulation allowed
⊙⊙⊙ No circulation allowed

Distance from warm face — cm
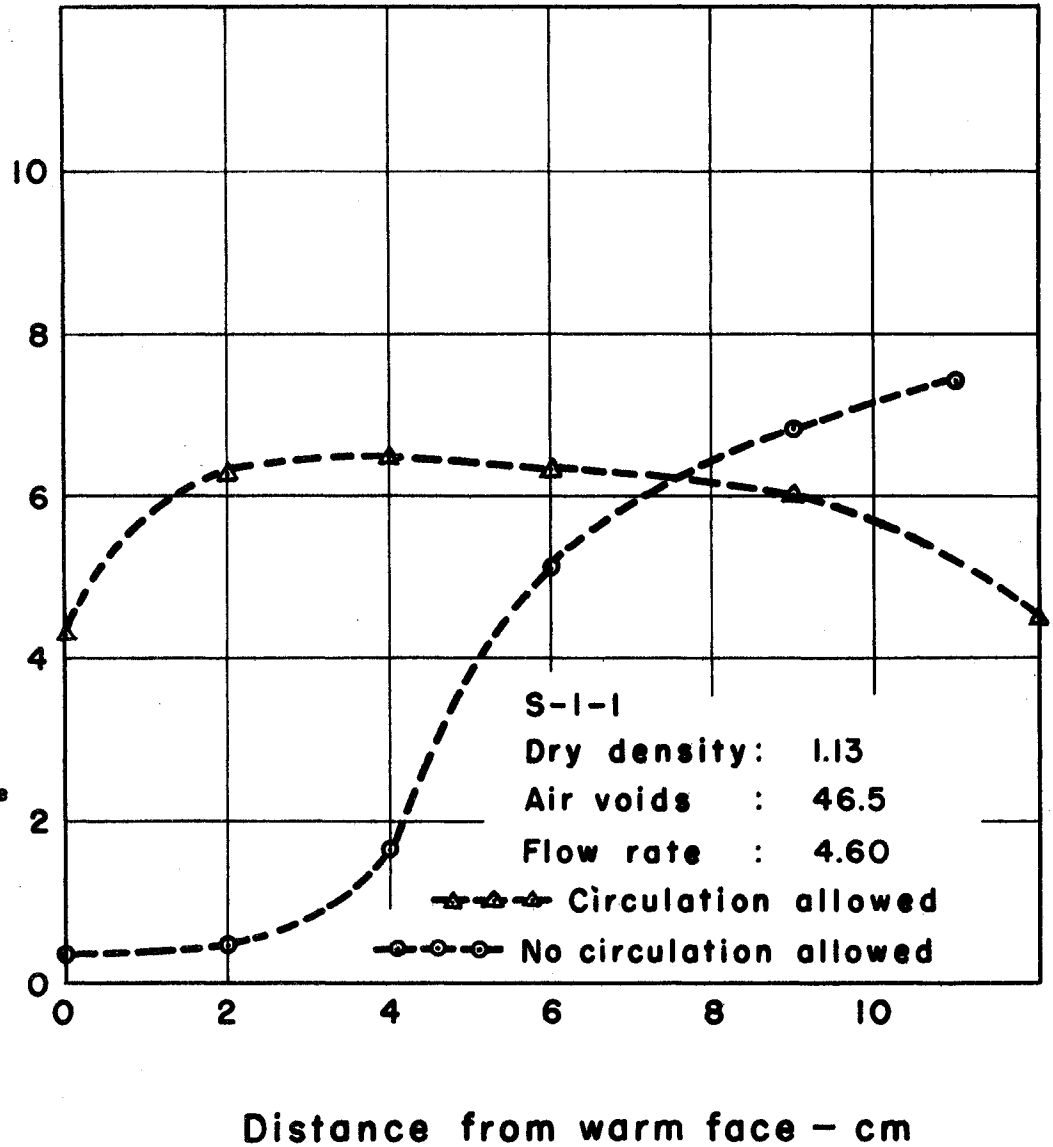
was uniform before the beginning of the experiment. The rate
of flow indicated here is a linear flow rate in a capillary
tube approximately 2 mm. in diameter for the circulating
system. In the non-circulating system, the moisture percent-
age at the end of the experiment was 4% and 26% respectively
for the warm and cold sides, indicating considerable trans-
fer of moisture. In the circulating system the flow rate
was approximately 5 cm. per hour and moisture distribution
throughout the length of the tube was approximately uniform
in comparison to that for the non-circulating system. There
is however, a characteristic lowering of the moisture content
on each end of the curve. This may be explained in the fol-
lowing way: 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 accumulated in the soil adjacent to the cold
porous plate. This causes a reduction in moisture content at
both ends. Eventually a steady state of flow is reached, and
the amount leaving the vicinity of the warm plate equals that
reaching the cold plate. The steady flow state is thus reached
with an adjustment of the moisture percentage along the tube
length. Any further tendency for reduction of the moisture con-
tent at the ends, ceases when the steady state flow condition is
reached. 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 reasoning given in Section II, moisture

which circulated through the external capillary tube during

the steady state should be moisture other than that which

moves through the soil continuously in the liquid phase.

Therefore, since moisture accumulated in non-circulating systems

and does not appreciably accumulate in the circulating system,

it seems that moisture movement in the liquid state is not the

predominating mechanism for this particular experiment.

Figures 7, 8, and 9 are the results of experiments very

similar to those portrayed by Figure 6. The essential differ-

ence has to do with the percent of air filled voids. These

values are approximately 26, 15 and 8 percent respectively

for Figure 7, 8, and 9. These figures show the same trend as

Figure 6, with moisture accumulation in the cold end for the

non-circulating system and a relatively uniform distribution

for the circulating system.

The effect of the density or percent of air filled voids

is observable from these figures. The rate of movement becomes

increasingly lower as the percent of air filled voids are reduced.

The density of the sample represented by Figure 9 is near
standard Proctor density and it is observed that the cor-
responding flow rate is very small.

It appears from experiments carried out this far that the
rates of flow in the circulating system can be maintained
indefinitely provided the thermal gradient is maintained, however
the length of time for any experiment has not exceeded ten 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 secre-
tions is believed to be the principal reason for the reduction
of permeability in the latter case. However, if the movement of
moisture is a molecular diffusion process, reduction in flow rate
would not be expected to the same extent as in saturated flow.

B. The Relationship between the Flow Rate, Thermal Gradient and Percent of Air Filled Voids

Flow rates for various densities were determined for
thermal differences in the range of $40° - 2°$ C., $30° - 2°$ C.,
$20° - 1°$ C., and $10° - 0°$ C. Data obtained from these tests
are tabulated in Table II. Moisture contents, dry densities,
mid-tube temperatures and the percent of air filled voids are
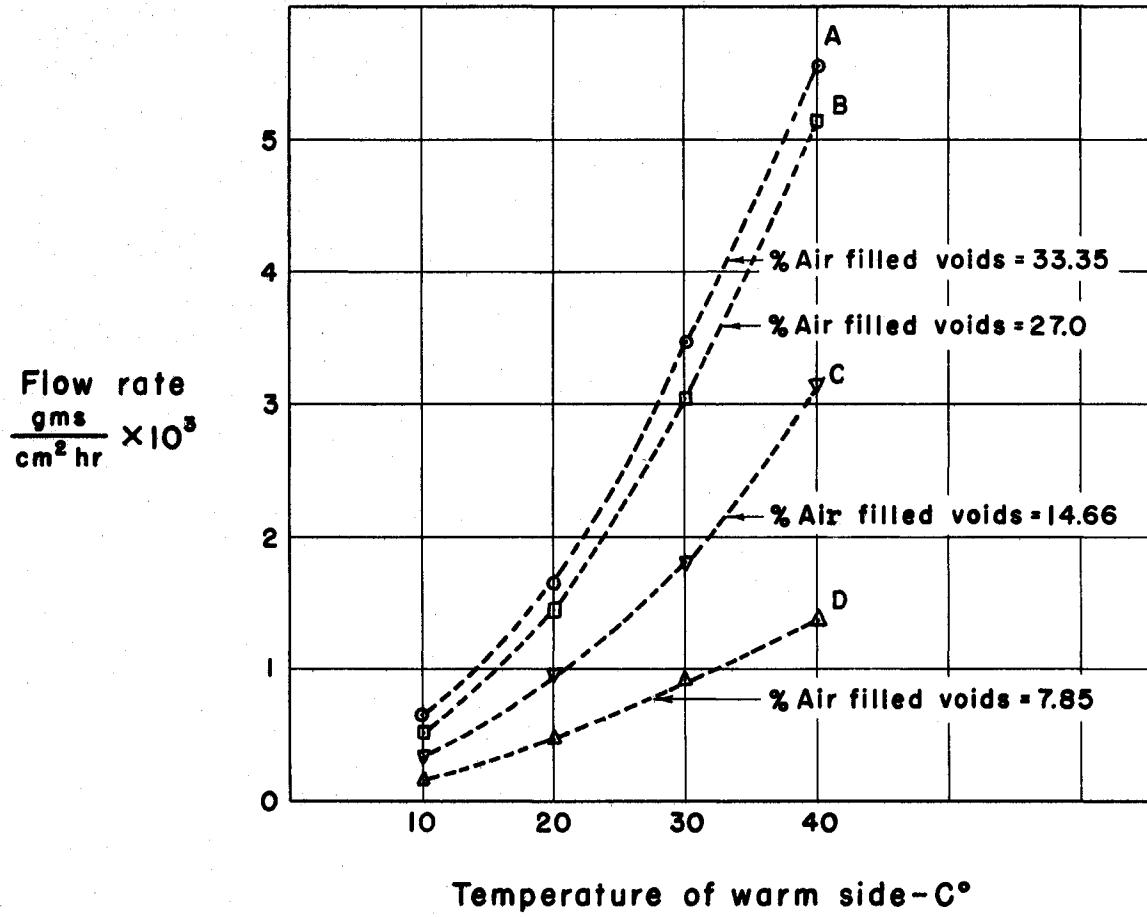also listed in this table. These data are shown graphically

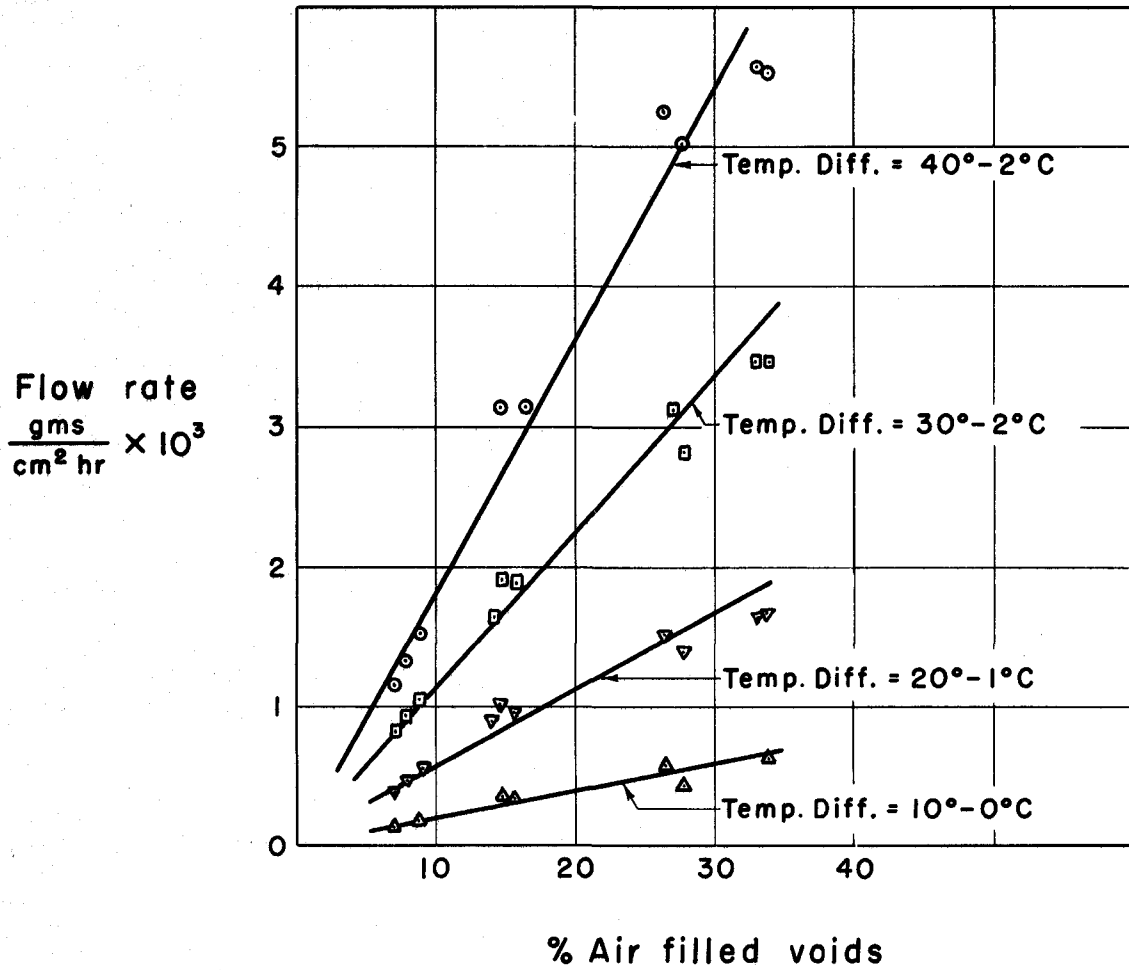Fig. 11. Relationship between flow rate and thermal gradient.

Fig. 12. Relationship between flow rate and percent of Air filled voids.

TABLE II. Relationship between Flow Rate and Thermal Gradient

Test No.	Percent H_2O	Dry Density	Percent Air Voids	Temp. Diff.	Mid-tube Temp.	Flow Rate Gm/cm^2 hr.
1	16.55	1.22	33.7	$40° - 2°C$	23.8	5.54×10^{-3}
				$30° - 2°C$	18.5	3.47×10^{-3}
				$20° - 1°C$	12.0	1.67×10^{-3}
				$10° - 0°C$	6.6	0.63×10^{-3}
2	16.55	1.23	33.0	$40° - 2°C$	23.8	5.58×10^{-3}
				$30° - 2°C$	18.5	3.47×10^{-3}
				$20° - 1°C$	12.0	1.64×10^{-3}
				$10° - 0°C$		
3	21.3	1.22	27.7	$40° - 2°C$	23.3	5.02×10^{-3}
				$30° - 2°C$	18.1	2.90×10^{-3}
				$20° - 1°C$	12.2	1.40×10^{-3}
				$10° - 0°C$	6.6	0.44×10^{-3}
4	21.2	1.25	26.3	$40° - 2°C$	24.2	5.27×10^{-3}
				$30° - 2°C$	18.6	3.12×10^{-3}
				$20° - 1°C$	12.3	1.505×10^{-3}
				$10° - 0°C$	6.6	0.59×10^{-3}
5	20.65	1.47	14.2	$40° - 2°C$	23.8	3.15×10^{-3}
				$30° - 2°C$	18.2	1.90×10^{-3}
				$20° - 1°C$	13.2	1.00×10^{-3}
				$10° - 0°C$	6.8	0.357×10^{-3}

TABLE II. Cont. Relationship between Flow Rate and Thermal Gradient

Test No.	Percent H$_2$O	Dry Density	Percent Air Voids	Temp. Diff.	Mid-tube Temp.	Flow Rate Gm/cm^2 hr.
6	21.00	1.456	14.0	40° – 2°C	23.2	3.16 x 10^{-3}
				30° – 2°C	19.0	1.63 x 10^{-3}
				20° – 1°C	12.0	0.902 x 10^{-3}
				10° – 0°C		
7	20.9	1.44	15.4	40° – 2°C	23.2	3.15 x 10^{-3}
				30° – 2°C	18.5	1.89 x 10^{-3}
				20° – 1°C	12.6	0.978 x 10^{-3}
				10° – 0°C	6.5	0.333 x 10^{-3}
8	20.34	1.585	7.9	40° – 2°C	23.0	1.344 x 10^{-3}
				30° – 2°C	17.7	0.914 x 10^{-3}
				20° – 1°C	12.0	0.468 x 10^{-3}
				10° – 0°C		
9	20.34	1.57	8.7	40° – 2°C	23.0	1.52 x 10^{-3}
				30° – 2°C	17.7	1.032 x 10^{-3}
				20° – 1°C	12	0.564 x 10^{-3}
				10° – 0°C		0.198 x 10^{-3}
10	21.1	1.58	6.9	40° – 2°C	23.4	1.29 x 10^{-3}
				30° – 2°C	18.3	0.827 x 10^{-3}
				20° – 1°C	12.4	0.392 x 10^{-3}
				10° – 0°C		0.14 x 10^{-3}

in Figures 11 and 12. The various values from tests 1 and 2
are averaged and plotted with flow rate on the ordinate and the
temperature of the warm side on the abscissa to give curve A
in Figure 11. Curves B, C and D are averages representing
tests 3 and 4, 5, 6 and 7 and 8, 9 and 10 respectively. These
curves show that the flow rate is not a linear function of the
temperature gradient for all values of the percent of air filled
voids. They also indicated that for a particular temperature
difference, the rate of change of the flow rate increases con-
siderably with the increase in the percent of air filled voids.

Figure 12 is a plot of the flow rate versus the percent
of air filled voids for various temperature differences listed
above. These curves indicate that the flow rate is a linear
function of the percent of air filled voids.

It is observed from Table II that there is quite a lot of
variation in the mid-tube temperatures for a specified temper-
ature difference. Since the temperature of the low side of the
apparatus could vary as much as 0.5° C. from the value specified
for that side, its effect on the mid-tube temperature masked
any effect which might be observed due to variations in density
and flow rate. It is observed however that in all cases the
mid-tube temperature is substantially greater than the mid-value
of the temperature difference, showing that the thermal gradient

is not a linear function of the length of the soil tube.
However, since the deviation of the temperature gradient
is not very far from linearity, an estimate of the tempera-
ture gradient at the mid-point of $38/10 = 3.8°$ C/cm for the
$40° - 2°$ C. temperature difference is believed to be a reason-
able approximation of the temperature gradient at that point.

With this approximation of the temperature gradient, the
amount of molecular diffusion through a unit cross section per
unit time at the mid-point of the tube may be estimated.
Considering test 1 with a temperature difference of $40° - 2°$ C.,
the following quantities are available for use in estimating
the flow rate.

$\alpha = 0.66$; $\phi = 0.337$; $T = 296.8°K$; $\dfrac{dT}{dx} = 3.8°$ C/cm

$L = 583.7$ Cal/gm; $P_v = 22.11$ mm. Hg.; $P = 760$ mm. Hg.

Substituting these values in equation (14)

$$q = 2.3 \times 10^{-6} \, \alpha \, \phi \, \frac{L \, P_v}{R \, (P-P_v) \, T^{0}.7} \, \frac{dT}{dx}$$

Results in $q = 3.01 \times 10^{-7}$ Gm/sec cm^2

The cross sectional area of the soil tube was 19.6 cm^2;
therefore the total flow is

$$Q = 19.6 \times 3.01 \times 10^{-7} = 0.59 \times 10^{-5} \text{ gm/sec}$$

The measured flow for this case was 3.02×10^{-5} gm/sec.

Considering test 9 and a temperature difference of $20° - 1°$ C. the resulting data is available:

$$\alpha = 0.66; \quad \phi = 0.087; \quad T = 283°K \quad \frac{dT}{dx} = 1.9° \ C/cm$$

$$L = 588.3 \ Cal/gm; \quad P_v = 10.518; \quad P = 760 \ mm. \ Hg.$$

Using these values the calculated value becomes

$$Q = 0.39 \times 10^{-6} \ gms/sec$$

The measured value is 3.07×10^{-6} gms/sec

These two illustrations which are typical of the relation between measured and computed values found in this experiment, seem to indicate that there is considerably more moisture moving than might be expected under the assumption of molecular diffusion.

VII. DISCUSSION OF RESULTS

A. Sources of Error

There are several possible sources of error associated
with the measurement in this experiment that should be
mentioned at this time. The first and probably the most
important as far as operation of the unit is concerned,
is that of providing proper contact between the porous
plates and the soil in the circulating system. If the
contact is poor with only a relatively small amount of soil
touching the plate, evaporation takes place directly off of
the plate and gives readings that are greatly in error. In
plotting moisture distributions as a function of the length
of the tube for a situation such as this, one finds that the
moisture content is greatest near the warm side and decreases
toward the cold side. If the porous plate is pressed too
firmly against the soil some local compression takes place
which will also affect the readings. Proper operation thus
requires that the soil is in intimate contact with the plate
without too much localized compression. The porous plates
were mounted in the end pieces so that when the soil tube
was placed between them and clamped securely a compression
of the soil in each end of the tube occurred to the extent
of about 1/32 of an inch. Clamping of the end pieces on to

the tube was accomplished with a goosenecked pipe clamp.
Examination of the soil at the completion of the experiment
showed the imprint of the plate in the soil. Moisture distri-
butions were also made for each sample at the completion of an
experiment to further confirm that adequate contact had been
made.

Another source of error inherently associated with
measurements using the apparatus described is that the vapor
pressure gradient is not a linear function of the temperature.
An examination of equation (14) indicates that in all proba-
bility the percent of air filled voids is not a constant value
for each point along the soil tube. This is substantiated by
the moisture distribution for the circulating system as shown
in figures 6, 7, 8 and 9. The exact amount of the error associ-
ated with the innate characteristics of the system is not ob-
tainable. It is believed that the reliability of the data from
experiments performed with this apparatus can be improved by
using a very small temperature difference over which the vapor
pressure gradient is essentially linear. Such measurements
would require a smaller capillary tube for the metering system,
a more precise method for controlling the temperature of the
cold side and a room where the temperature can be controlled
very accurately.

B. Liquid Versus Gaseous Flow

Results of this experiment as shown in Figures 6, 7, 8 and 9 substantiate the belief that the predominant mechanism of moisture migration is associated with vapor movement of some manner. It should be emphasized however, that the soil used in this experiment was a silt with a low cation exchange capacity and that the conclusion arrived at pertains strictly to that soil. No data has been presented that would refute the possibility of movement of some moisture in the liquid phase in a heavy clay soil.

C. Differences between Measured and Estimated Values

In the computation of the estimated amounts of flow, values of the diffusion constant and the structural factor were taken from the results of previous investigators. Part of the discrepancy between measured and estimated results may be ascribed to possible inaccuracies of these values.

A mechanism such as that proposed by Smith (20) if it occurred, would be susceptible to measurement in the apparatus used here. A part or all of the discrepancy might be attributed to some other mechanism other than molecular diffusion, such as that proposed by Smith.

Although it is believed that the measurement of the amount
of flow in the apparatus used here represents a true movement
of soil moisture under a thermal gradient, it is recognized
that some inherent error in the system similar to those
previously mentioned may invalidate the formula used or in
some other way be responsible for the discrepancies involved.

VIII. CONCLUSIONS

An apparatus for measuring the rate of migration of soil moisture due to a thermal gradient has been described. A hypothesis for determining the relative importance of flow in the vapor phase as compared to movement in the liquid state is presented. The results of comparisons of the moisture distributions in circulating and non-circulating systems tend to substantiate the belief that the predominant method of movement of soil moisture is associated with vapor movement.

A comparison of calculated flow rates for a molecular diffusion process with observed values shows the measured values are several times the calculated rates.

Flow rates were determined for temperature differences of $40^\circ - 2^\circ$ C., $30^\circ - 2^\circ$ C., $20^\circ - 1^\circ$ C. and $10^\circ - 0^\circ$ C. for a number of different values of the air filled voids. These data indicated that the flow rate is a non-linear function of the temperature gradient and that amount of moisture movement per unit time seems to vary linearly with percent of air filled voids.

IX. BIBLIOGRAPHY

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X. ACKNOWLEDGMENTS