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THE INFLUENCE OF TEMPERATURE GRADIENTS ON SOIL MOISTURE FLOW

by

Luigi Cavazza

A thesis submitted in partial fulfillment
of the requirements for the degree

of

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in

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Luigi Cavazza was born at Bari, Italy on November 18, 1923, a son of Ferdinando Cavazza and Lidia Schutz.

After the primary and secondary instruction, he attended the School of Agriculture at the University of Bari (Italy). In 1946 he obtained the doctor degree in agricultural sciences, discussing a thesis on the agricultural applications of phytohormones. Later he was assistant at the same University. In 1950 he obtained a scholarship to the Institute of Plant Physiology of the School of Technology in Zurich, Switzerland. He also studied in the Soil Physics department of the Rothamsted Agricultural Experimental Station, Harpenden, Herts, England. He came to United States under a Fullbright scholarship, supported by a government grant.

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INTRODUCTION

The isothermal movement of liquid water in saturated soil has been intensively studied, and a sound theoretical basis has been developed. Considerably less is known about the flow of water in unsaturated soils, but a general theory based on Darcy's law of flow is beginning to develop. A good theoretical basis exists for the vapor diffusion under isothermal conditions. Inconsistent data and theories are found in the literature concerning the movement of water in both the vapor and liquid phases, under the influence of thermal fields.

The soil is subjected to periodic fluctuations in temperature. Within the profile there almost always exists temperature gradients that are constantly changing at different depths and times. The importance of a better knowledge of the phenomenon is therefore evident. This is particularly true for semiarid regions where the temperature variability is generally high and the moisture balance of the soil has an important role in crop production.

It is the purpose of the study reported herein to investigate some of the characteristics of soil moisture movement that result from temperature gradients.

REVIEW OF EXPERIMENTAL LITERATURE

Since the beginning of this century, and particularly under the influence of the German school (e.g. Zunker (1930) etc.) it has been assumed that there is an upward movement of moist air during the night from the warmer soil below to the colder soil at the surface where the vapor is condensed. Bouyoucos (1915) says that at that time this theory seemed very widely accepted. According to him, Hilgard stated that dew is formed from vapor rising from the warmer soil into a colder atmosphere, and condensed on the most strongly heat-radiating surface near the ground, such as grass; leaves, both green and dry; wood; and other objects first encountering the rising vapor.

The first experimental work made in order to check the hypothesis of a movement of water in vapor phase under thermal influence, seems to be that of Bouyoucos (1915).

The technique adopted by Bouyoucos consisted in keeping a sealed cylinder filled with soil, one half immersed in a cold water bath and the other half in a warm bath for a period of eight hours.

The results showed that the amount of moisture transferred is a function of the difference in temperature of the baths, the type of soil, and the initial moisture content of the soil. There was an optimum moisture for water movement; this optimum varied from 7.5% (light sandy loam) to 19.29% (clay) when the difference in temperature was 20° C. The corresponding maximum displacements of water were from 0.9% (light sandy loam) to 1.19% (silt loam). With 40° C. difference in bath temperatures these figures shift to 2.88 and 3.68.

Bouyoucos's interpretation was that the adhesive forces of the soil for the water were responsible for these results. Changes of viscosity and surface tension could not account for any departure from the initial moisture. He explained that at low moisture percentage the warm soil did not release water, since its attractive force was not satisfied. At the optimum moisture, the warm soil lost its water more easily, while the cold soil exerted a high pull because of a higher surface tension and particularly a high attractive force (assumed inversely related to the temperature). At a higher moisture percentage the water could still be lost easily by the warm soil, but the attractive force of the cold soil was already saturated and only the small influence of the surface tension was evident.

The results of Bouyoucos (1915) showed a surprising small transfer of water. In order to isolate the influence of the temperature-gradient on the liquid and vapor phase, he interposed two wire screens between the two halves of the soil column, this provided an air space 1/4 inch thick. After 8 hours of the same treatment previously described, the amount of the water transfer appeared to be still lower, giving an average of 0.035% at 20° C. difference between the baths, and 0.25% at 40° C. difference. Bouyoucos suggested that the vapor movement has a very little influence and under natural soil conditions should be neglected.

In 1937, a paper by Lewis dealt with the vapor flow in the soil at isothermal conditions. The soil column was constantly wet at one end while evaporating in free air at the other end. He used two screens (30 mesh) about 1 mm. apart in order to break the soil column. In this case, like that of Bouyoucos, the breaking of the column greatly retarded the evaporation rate from the open end of the soil core.

In the same year Curtis (1937) wrote (but did not prove) that it was not clear that Bouyoucos's technique for distinguishing between vapor and liquid flow was entirely sound.

Later on, Smith (1939, 1943) criticized the procedure of Bouyoucos. In those conditions the thermal gradient could not be determined and was certainly not uniform at different distances from the cylinder wall and from the dividing plane. Furthermore, the gradient was presumably distributed through a narrow distance, so that the water could easily move from cold to warm in this narrow region, but then, Smith said, it could hardly move farther. For this reason, the moisture displacement, referred to the whole of the half column (4" long) was very low. A period of 8 hours also seemed to be too short.

Smith conducted analogous experiments with an apparatus for thermal conductivity determinations, i. e., using a continuous soil column only 3/4" or 1" long. The experiment lasted about 24 hours. The results agreed qualitatively with those of Bouyoucos. However, the water transfer at the optimum initial moisture (50% of moisture equivalent) reached about 100%, i.e. much more than that of Bouyoucos. Using fragmented soil samples instead of monolith cores, the moisture transfer increased and the optimum moisture was somewhat displaced.

In his conclusion Smith (1939) said:

> It is felt that this vapor movement is a mass transfer of vapor caused by convection rather than diffusion, since the latter is too slow a process. Changes in surface tension of the liquid forming capillary surfaces on the cold and warm sides of the plate are too small, for the thermal gradient applied, to account for any considerable movement of water.

Later (1943) the same writer performed a similar experiment modified in order to check the hypothesis of a vapor movement. He again interposed between the cold plate and the soil sample a coarse wire gauze, creating an air gap approximately 1 mm. thick. This air chamber permitted the drainage of any eventually condensed water. The difference of temperature between the plates was 40° C. giving a thermal gradient of about 20° C./cm. After 4 days, no water drainage was observed and only a moderate amount of condensed moisture was found at the cold surface. The moisture transfer in the sample (initially at moisture equivalent) was only 0.5%. Smith concluded that:

> If the behaviour were wholly due to vapor transfer, be it diffusion or convection, it would appear that it ought to proceed continuously. It should commence as soon as any water was present in the soil, and continue until transfer to colder regions had taken place.

This writer, therefore, turned to an explanation of the phenomenon based on capillary forces in liquid form. We shall consider this theory in detail later.

In 1927 a detailed study by Lebedeff (1927) appeared. It was concerned with the balance and movement of soil water under field conditions and reported some results of laboratory tests on the influence of the temperature. He supported the idea that a cool spell during the summer not accompanied by rain, which is followed by a hot period, may result in considerable losses of water from the deeper layers. The cooled surface draws the water up and the folllwing hot spell again moves the moisture on out of the soil. These statements were made on the basis that at Odessa (Russia) 66.2 mm. of water were moved from the deeper horizon during the winter. These figures were obtained from an accurate accounting of evaporation, precipitation and soil moisture determinations at different depths. The water was assumed to move in vapor phase along gradients resulting from difference in vapor pressure at different depth in the soil, as calculated from the temperature readings.

It can be easily observed that Lebedeff certainly demonstrated the moisture transfer due to temperature gradients, but by no means could he be sure that this displacement took place in the vapor rather than in the liquid phase.

In 1940, an interesting paper by Krischer and Rohnalter (1940) appeared in Germany, but has received no attention by soils investigators. Krischer and Rohnalter were primarily interested in thermal conductivity determinations on porous materials (particularly stones,"Ziegelstein"). From previous results and from data of other German researchers, these writers had observed a relevant disturbance in thermal conductivity determinations, by the interference of moisture transfer. In their experiments they demonstrated that when two clay-plates are kept constantly saturated and isolated by an air layer, and when the two plates are maintained at different constant temperatures, the vapor flows from the warm to the cold plate, as expected. However, if the border of the plates are connected together by a thick layer of blot-paper, the water will flow back as a liquid from the cold to the warm plate by capillarity. In this way the circuit is completed. They concluded that this happens also in porous consolidated or loose materials. A rather exhausting mathematical discussion was applied in order to explain and calculate the thermal diffusion coefficient. These writers, however, while dealing with the moisture flow, limited their discussion to equating the expression for vapor flow to that for liquid flow. They assumed that the fluid flow is proportional to the moisture gradient and that the permeability constant is function of the moisture content.

Later MacLean and Gwatkin (1946) and Croney and Coleman (1947), quoted by Gurr et al. (1952), confirmed the moisture transfer under the temperature gradient. McLean and Gwatkin 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.

In 1947 Winterkorn (as quoted by Gurr et al., 1952) developed a theory of film flow of liquid water from the hot to the cold ends, along the internal surface of the porous soil system, due to change in water affinity with change in temperature. He considered this to be a more important mechanism than vapor movement. He also observed an electric potential difference in the soil due to the temperature gradient and suggested that the thermal water movement may be a special case of electro osmosis.

In 1952 Brawand and Kohnke, studying the water balance in field conditions confirmed the results of Lebedeff. They assumed, without proof, that the movement of water under the thermal gradient occurred in the vapor phase.

Jones and Kohnke (1952) also repeated the experiment of Bouyoucos with the same technique, but only with continuous soil column. Their results agree with Bouyoucos's results, but show an important moisture flow only near the central section, where the gradient really existed. They also assumed, without any experimental proof, that the flow had taken place in vapor phase.

Recently, Gurr, Marshall and Hutton (1952) by a different technique and independently confirmed the finding of Krischer and Rohnalter. They had a soil column 10 cm. long, between two plates at different temperatures. The soil samples were artificially provided with a high salt content. After periods of 5 or 10 or 13 days, the soil was analyzed at different distances from the column end, for moisture percentage, salt content and Cl^- ion content. Although the data on salt content were generally inconclusive, the distribution of Cl^- showed an evident accumulation at the warm side, while the moisture was accumulated at the cold side, as expected. The writers concluded that while the vapor flows from warm to cold, the liquid water flows back from cold to warm forming a closed circuit.

Considering the literature on this problem, as a whole, although the theory and the results of Krischer *et al*. and Gurr *et al*. seem clear and sound, one is struck by the contradiction with the other results.

It is remarkable that, while the use of wire gauzes seems to be the most natural way of distinguishing the vapor from the fluid flow, all the writers that used this method failed to detect any important vapor flow. Furthermore, no serious criticism has been made to this technique.

On the other hand, Krischer and Rohnalter alone demonstrated directly the back flow of liquid water. However in their case the vapor could move very easily in a free air space. This does not happen in the soil. Their theory does not take into consideration the tension at which the soil moisture is held.

In the work of Gurr *et al*., the salt content data are not consistent which casts a shadow on the reliability of the Cl^- ions distribution. We do not know the location of the cations. Even though considerations of difference in concentration as a function of the temperature and the expected ion distribution following the setting up of a streaming electrical potential, seem to support Gurr's conclusion, there still exists some doubt as to the true facts.

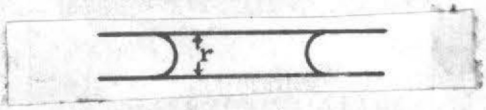
Gurr et al., also, computed (but no details are given) a diffusion coefficient for the vapor phase, much higher than could be expected from Penman's equation for gaseous diffusion. From their data it seems also that the hydraulic conductivity of their soil is rather high, since at about 12.5 to 16 percent moisture the observed final moisture gradient was practically zero, while the Cl^- accumulation (and therefore the water movement) was high.

From what is said above, the following points seem worthwhile to check and explain adequately.

1. Causes of failure of the air-gap technique.
2. Factors causing the high diffusion value found by Gurr et al.
3. The value of the moisture conductivity under these conditions.
4. Distinction between diffusion and convection movement in the vapor phase.
5. Wider theoretical basis of the observed phenomena.

REVIEW OF THEORETICAL LITERATURE

Smith (1943) considers the difference of the attractive force acting on the menisci at the end of a capillary tube under a thermal gradient. This difference is given by the formula:



$$\Delta T = 2\pi r\gamma - 2\pi r\gamma(1-\alpha\Delta t)$$

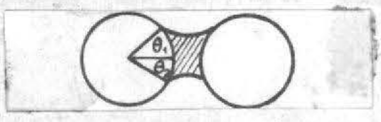
$$= 2\pi r\gamma\alpha\Delta t$$

Fig. 1

Water in a capillary tube.
From Smith (1943)

where Δt = difference in tension; r = capillary radius; γ = surface tension; Δt = difference in temperature; α = thermal coefficient for γ. There is equilibrium only at $\Delta t = 0$.

For the water held between two spherical particles the formula is at first approximation:



$$\Delta T = \pi r\gamma\cos^2\theta_1 - \pi r\gamma(1-\alpha\Delta t)\cos^2\theta_2$$

Fig. 2

Water between two spherical particles.
From Smith (1943)

and the equilibrium conditions are:

$$\Delta t = 0 \qquad \text{or for } \Delta t \neq 0: \qquad \cos^2\theta_2 = (1-\alpha\Delta t)\cos^2\theta_2$$

Smith notes that for $\Delta t = 10°$, $\alpha = 0.0016$, θ_1 and θ_2 are practically equal and therefore in the soil, if this scheme applies, no practical movement occurs.

The following mechanism is proposed by him for explaining the liquid movement another way. First evaporation occurs at the warm side. This vapor condenses on the wet soil layer. If here there are two water menisci separated by an air gap and sufficiently close, resulting from the vapor condensation, they may coalesce. The new bigger water mass will find new equilibrium conditions by moving under ordinary capillary forces, toward the cold end in the immediately nearest pore. The vapor condensation is assumed to play only the role of a trigger to start the process. This process is thought to continue until only rings of "pendular" water are left in the warmer soil. This mechanism will not occur if the menisci are too far apart for coalescing (i.e. low moisture content) or if the pores are saturated so that a continuous liquid phase exists (i.e. high moisture content).

Baver (1940) recognizes that "the explanation by Smith of the trigger effect on the vapor condensation is an intriguing one." This explanation has two serious weaknesses. 1. It is not clear how the menisci may coalesce, since each soil mass limited by two opposite menisci is expected to receive at the warm side the same amount of vapor that it should lose at the cold side by evaporation (transfer to a colder layer). 2. Even assuming that coalescence occurs, it is not understandable why the new equilibrium position has to be found only by moving toward the cold side. Since Smith himself admits that the importance of differences in γ is very little in a system of spherical particles, it seems likely that in the soil the movement is chiefly determined by differences in the tension due to the geometrical configuration of the pores. Therefore, if movement will occur, it will have equal probability to occur in any direction, when a random pore distribution exists.

Mickley (1949) assumed that the water is held in the soil in the form of independent droplets. Under a temperature gradient, a droplet is distorted, and may coalesce with another droplet. The distortion is assumed to be proportional to the gradient. The new mass will move to find an equilibrium position in a crevice toward the cold side. Occasionally two or more droplets may meet and coalesce after they first start to move. Assuming a regular triangular arrangement of the soil particle, he computed that the probability that the space between two particles is occupied by a water droplet is:

$$\frac{\text{total number of droplets}}{\text{total number of spaces}} = \frac{\text{initial moisture content}}{\text{field capacity}} = \frac{M}{F}.$$

For a merging, two adjacent spaces must be filled, the probability of this occurring is $(\frac{M}{F})^2$. No merger will occur if all the pores surrounding a particular cell are already filled with water; this event has a probability $(\frac{M}{F})^5$. The probability of a merger is therefore $(\frac{M}{F})^2 - (\frac{M}{F})^5$. The moisture transfer is given, according to Mickley, by the expression $M = K \frac{dt}{dx} \left\{ (\frac{M}{F})^2 - (\frac{M}{F})^5 \right\}$. This formula seemed to agree rather well with most of the experimental data of Smith. Here also, however, many of the criticisms made to

Smith are applicable. In Mickley (1949), Mansfield seriously criticised many of the assumptions, particularly that of the droplet state of the water and the rather arbitrary computation of the probability factors. He also pointed out that if the moisture transfer depends only on the thermal gradient, only a dry soil layer at the warm end and a wet layer at the cold end are expected, the soil at the uniform initial moisture content being intermediate.

THEORY

Consider a cylindrical column of soil initially at uniform moisture. Place it in a thermal field, such that there is a uniform temperature gradient along the axis of the cylinder, the temperature being equal and constant in any transversel section.

The temperature of the system and its gradient will influence the physical properties of all three phases. Since, however, the thermal expansion of the solid phase seems to be negligible for our purposes and assuming that the structure and other physical properties of the solids are negligibly affected by the temperature, the discussion will be confined to the liquid and gaseous phases.

Liquid Flow

First consider a simple picture of the temperature effect on the liquid phase.

Assume that the water is held in the soil under a stress resulting from four recognized components:

$$\Phi = gh + \psi + \pi + \omega \tag{1}$$

where Φ = total stress; gh = gravitational component; ψ = capillary potential; π = osmotic pressure potential; ω = component due to the adsorptive forces at the solid-liquid interface; all expressed as energy per unit mass of water. By choosing a suitable reference plane and for small differences in h compared with the other components, gh may be neglected. The π component has no effect on the moisture flow at high moisture contents, since only negligible restraint is present on the dissolved materials. At rather high moisture content the term ω may also be neglected. At all moisture levels the effect of ω is assumed to be independent of the temperature. The component ψ remains, it can be represented in a smooth pore or capillary by:

$$(2) \qquad \psi = \frac{2\gamma}{rp}$$

where γ = surface tension of the water; r = pore radius; p = density of the water.

The general law for the liquid flow (Darcy's law) may be written:

$$(3) \qquad \frac{dq}{dt} = -K \frac{d\psi}{dx} .$$

But where q is the quantity of water flowing across a unit area perpendicular to the x direction in time t, and K is the hydraulic conductivity. But γ is a function of the temperature as follows:

$$(4) \qquad \gamma = AT - B \quad (T = \text{absolute temperature.}).$$

Also $\frac{d\psi}{dx} = \frac{2}{rp}\left(\frac{dx}{dT} \quad \frac{dT}{dx} \right)$ and $\frac{dx}{dT} < 0$. Therefore from (3) we expect to have a water flow in liquid phase from warm to cold under the influence of a thermal gradient. This flow will cease as soon as ψ becomes equal throughout all the soil column, as a result of change in the moisture distribution. This distribution will depend on the soil moisture-tension relationships, which are characteristic of a given soil.

A numerical example will illustrate the order of magnitude of this movement. Assume a thermal gradient of 1.5° C./cm. and a length of 10 cm. for the soil column. A relative difference of about 3.20% for γ at the cold and warm end may be computed. From the soil moisture retention curve for the Millville silt loam (fig. 22) it can be shown that at 18% average moisture content of the soil sample, a difference of only 0.024% may exist for the moisture content at the ends of the column. For 10% average moisture, a difference of 0.196% is computed. These figures are evidently too low to account for any significant movement.

A factor that has generally been disregarded is the thermal expansion of the water. This factor acts in two different ways. First it changes the value of the density of water (ρ) in equation (2) and therefore tends to increase the tension at the warm side, opposing the action on γ . But more important is the effect of the relative expansion of the water between the solid particles. Since no data are available for the thermal expansion coefficient of the soil minerals, this coefficient for water is compared with that for glass, assuming that the soil silicates will have a coefficient of about the same order of magnitude.

Temp. range	coeff. of therm. expans. x 10^5		differ. x 100
	water	glass	
5° - 10° C.	5.3	2.5	0.0028
10° - 20° C.	15.0	2.5	0.0125
20° - 40° C.	30.2	2.5	0.0277

(Intern. crit. tables.)

From these data it is evident that a change in temperature will make the water expand more than the solid phase and therefore the menisci will extend outward from the pore cells, and the tension of the water will be decreased, resulting in a movement of water. This water flow will cease when the moisture distribution has reached equilibrium on a volume basis rather than on a weight basis.

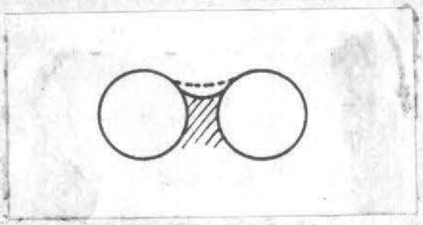


Fig. 3

Thermal expansion of water in the soil.

Referring to the previous numerical example, a difference in moisture content of about 0.020% is computed at the 18% average moisture content as a result of thermal expansion.

The influence of changes in viscosity of the water is neglected herein. This factor plays no role in the final distribution of the moisture, but it influences only the time required to reach the equilibrium.

It is concluded therefore, that some influence is theoretically expected in the liquid water distribution under the influence of a thermal gradient, but its magnitude, even after adding all the components, is negligible

Vapor Flow

Look now to the gaseous phase. First consider the change in density brought about by a temperature difference. This results from two factors. The thermal expansion of the air reduces its density. Since the thermal expansion coefficient for gases is about $\frac{1}{273}$, the density is inversely proportional to the factor $(1 + \frac{\Delta T}{273})$, where ΔT is the difference in temperature. This difference in density along the soil column, brings about a pressure gradient that can be expressed by the following equation

$$\frac{\Delta p}{\Delta x} = \frac{p - \dfrac{p}{(1 + \frac{\Delta T}{273})}}{\Delta x} = \frac{\dfrac{p\Delta T}{273}}{\Delta x \left(1 + \frac{\Delta T}{273}\right)}$$

As the limit is approached:

$$\frac{dp}{dx} = \frac{p}{273\ (1 + \frac{\Delta T}{273})} \quad \frac{dT}{dx} = \frac{p_1}{273} \frac{dT}{dx}$$

Consequently the air will flow from the region of higher density (cold side) to that of lower density (warm side).

This fact is complicated by the presence of the liquid phase. Temperature increases the saturation vapor pressure of the water, at the warm side. This will increase the amount of vapor per unit volume of air. This will also tend to decrease the density at the warm side. The combination of both effects must be taken into consideration.

Referring to the previous example, and assuming temperatures of 13° C. and 28° C. at the two ends, with an atmospheric pressure of 640 mm. of Hg, the moist air density at the column ends is 0.001032 and 0.000971. However, the effective air flow through the soil, from cold to warm, can not be calculated since the air-permeability of the soil is unknown.

This air flow, due to a temperature difference is convection flow. Since the air mass moving from warm to cold along the upper part of the soil column is saturated (soil moisture = 18%), it will lose vapor as it cools. This condensation will occur along the stream from warm to cold, while evaporation is expected to occur along the stream-lines from cold to warm. Also, the convection movement will be added to the diffusion movement in the upper part, while it will be subtracted from it in the lower part of the cylinder. Therefore a difference in soil moisture can be expected in the upper and lower layers of the column.

An important effect of the temperature seems to be related to changes in the partial vapor pressure at saturation. The vapor pressure of the water vapor in the soil is of course also related to the water tension in the liquid phase. Consider the case of soil moisture higher than the wilting percentage. The relative humidity of the soil air may be considered practically equal to 100% and independent of the soil moisture content.

If the soil is kept under uniform thermal gradient, a vapor pressure gradient will result and the vapor will flow by diffusion from the higher pressure region (warm end) to the lower pressure (cold end). Since the vapor is saturated at every point of the column, it may be predicted that, while flowing to colder regions, the vapor can no longer be contained in the air at the same concentration and a part of the vapor will condense.

The vapor pressure- temperature relationship is not a linear one. It may be expressed by the following equation:

(5) $$\log_{10} p_0 = \frac{-A}{T} + B. \; [1]$$

where T = absolute Temperature and, for water, A = 2309.3 and B = 9.124. The curve is shown in figure 11.

From what has been said, it is evident that the rate of change per temperature degree of the vapor condensation during diffusion, is proportional to the derivative of the vapor pressure:

(6) $$p_0' = \frac{dp_0}{dT} = \frac{-A\,p_0}{T^2 \log_{10} e} > 0 \qquad \begin{matrix} \text{for } p_0 > 0 \\ 0 < T < \infty \end{matrix}$$

and the rate of change of condensation per unit distance will be proportional to:

(7) $$\frac{dp_0}{dx} = \frac{dp_0}{dT} \quad \frac{dT}{dx}$$

Since p_0' is a function of T, and from (6) and (7), we see that the rate of condensation is not equal throughout the soil column, but is greater at the higher temperatures. This means that, assuming a soil column of indefinite length, with continuous vapor supply at the warm side and without impediment to the vapor flow at the cold side, the soil moisture will increase at each point, but at a higher rate when the temperature at that point is higher.

The diffusion of the vapor through the soil, like that of other gases, obeys the general law:

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[1] A more exact equation is: $\log p = \frac{A}{T} - B \log T + C$. Since in the range of temperature applied, the first equation fit almost exactly to the data given in various reference tables, it is used herein.

(8a) $$\frac{dq}{dt} = -D\,\frac{dp}{dx}$$

where q = amount of vapor crossing the unit area in time t, and D = diffusion coefficient. Since in this case $x = f(T) = kT$, and $p = p_o$, we may write:

(8b) $$\frac{dq}{dt} = -K\,\frac{dp_o}{dT}$$

From (6), p_o' is $f(T)$, therefore the vapor flow is not uniform and there is divergence in the flow. We have:

(9) $$p_o'' = \frac{d^2p_o}{dT^2} = Ap_o\,\frac{\frac{A}{\log_{10} e} + 2T}{T^4 \log_{10} e} > 0$$

$$\text{for} \begin{cases} p_o > 0 \\ T < \dfrac{-A}{2\log_{10} e} = 2658^\circ \text{ K} \end{cases}$$

This indicates that in the ordinary range of temperature there is accumulation at every point. This accumulation is given from 8b by:

(10)
$$\frac{\partial}{\partial x}\left(\frac{\partial q}{\partial t}\right) = -K\,\frac{\partial}{\partial x}\left(\frac{\partial p_o}{\partial T}\right)$$

or

$$\frac{\partial^2 q}{\partial t\,\partial x} = -K\,\frac{d^2 p_o}{dT^2}$$

Also:

(11) $$p_o'' = \frac{d^3p_o}{dT^3} = \frac{-Ap_o}{(\log_{10} e)^3} \cdot \frac{(A + 3T\log_{10} e)^2 - 3(T\log_{10} e)^2}{T^6} > 0$$

$$\text{for } 0 < T < \frac{-A}{(3+\sqrt{3})\log_{10} e} = 1132^\circ \text{ K}$$

$$\text{or} \qquad T > \frac{-A}{(3-\sqrt{3})\log_{10} e}$$

which indicates that the accumulation is higher at the higher temperatures.

Only the idealized open column has been considered. Now turn to the case of a closed system, like that generally used in experimental work.

As soon as the vapor starts to flow, the relative humidity at the warm end decreases thus encouraging evaporation from the liquid phase. Similarly at the cold end, when new vapor masses arrive, condensation will occur. For stationary conditions it is required that:

evaporation rate = diffusion rate = condensation rate.

A theoretical formula for evaporation in still air from Int. Crit. Tables is:

$$V = K_1 \log \frac{p_A - p}{p_A - p_o} \qquad \text{(12a)}$$

where V = volume evaporated per unit time; K_1 a constant depending on the diffusion coefficient and the area; p_A = the overall gas pressure; p_o = vapor pressure at saturation; p = vapor pressure in the gaseous phase.

A similar empirical formula, used for many purposes (in meteorology, industry etc.) is of the type:

$$\frac{E}{A} = K\,(p_o - p) \qquad \text{(12b)}$$

where $\frac{E}{A}$ = weight evaporated per unit time and unit surface; $p = p$ of equation (12a); K is a proportionality constant, found for evaporation in still open air $\simeq 0.02$. For simplicity (12b) will be used rather than (12a).

In the case under consideration, the diffusion rate and the temperature at each point are independent variables, and are constant for each point. Adjustment of the evaporation rate may be obtained only by variation of the relative humidity and by changing the area of the air-water interface involved in evaporation.

On the other hand the vapor pressure gradient inside the evaporation region must change with the distance from the warm face according to the amount of vapor crossing any given section. This amount of vapor is the sum of all the water evaporated from soil that is warmer than the given section. This is shown in fig. 4. From the above arguments the evaporation equation may be written:

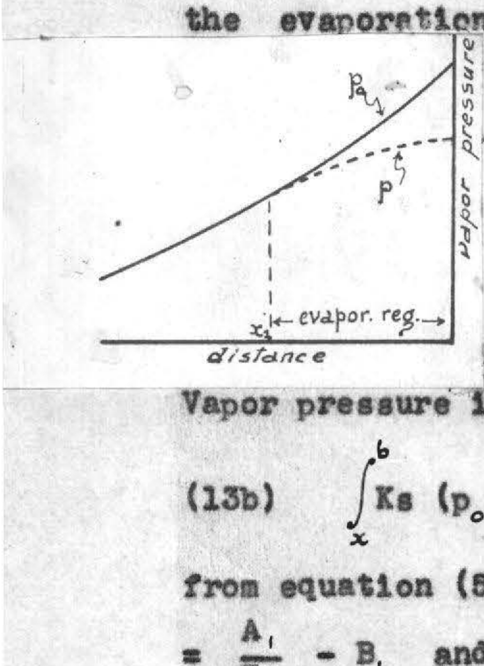

Fig. 4

(13a)

$$E = \int_{x_1}^{b} Ks\ (p \quad - p)dx$$

and for an intermediate section (see equat. (8a):

Vapor pressure in the evaporating region

$$(13b) \qquad \int_{x}^{b} Ks\ (p_o - p)\ dx = -D \frac{dp}{dx}$$

from equation (5) and for $x = f(T) = kT$, we have $\log\ p = \frac{A_1}{x} - B_1$ and $x = \frac{A_1}{\log_{10} p_o + B_1}$

therefore (13b) becomes:

$$-Ks\ (p_o - p) = -D \frac{d^2p}{dx^2}$$

$$(13c) \qquad Ksp - \frac{Ks}{e^{B_1/\log_{10} e}}\ e^{A_1/x\ \log_{10} e} = -D \frac{d^2\ p}{dx^2}$$

This differential equation of second order is of the type:

$$a\, e^{\frac{1}{x}} - by = \frac{d\,y}{dx}$$

Unfortunately no one of the methods tested, permitted the solution of this equation.

Consider now the conditions at the cold end of the soil column.

Condensation obeys the same law as evaporation (see equations (12a) and (12b)), there also the rate of condensation will depend on the degree of supersaturation and on the surface involved. In this case the quantity of vapor crossing a given area inside the condensation zone must be equal to the difference between the amount of diffusion along the soil column, minus the vapor already condensed in the previous sections. The slope of the super-saturation curve, therefore, is zero at the cold face, and gradually changes until reaching the value of the p_s curve when no condensation occurs. This is shown in Fig. 5.

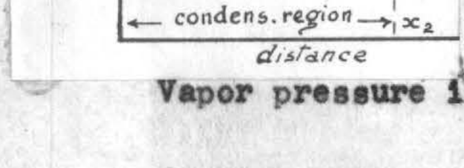

Fig. 5

From equation (12b) and the above arguments the condensation equation may be written:

Vapor pressure in the condensing region.

$$\text{(14a)} \qquad C = \int_a^{x_2} Ks\ (p - p_o)\, dx.$$

and for an intermediate section (see equation (8a)):

$$(14b) \qquad \int_a^x Ks\ (p - p_o)\ dx = -D \frac{dp}{dx}$$

From (5) we have:

$$\frac{Ks}{e^{B_1/\log_{10} e}}\ e^{A_1/x \log_{10} e} - Ksp = D \frac{d^2p}{dx^2}$$

this is the same as (13c).

Summarizing; the following factors are involved in the moisture transfer in vapor phase, when a closed system is used:

1. air-convection. Higher moisture movement is expected in the upper half of the column.
2. condensation by decrease of saturation vapor pressure; it is expected to be greater at the higher temperatures.
3. condensation by decrease of the rate of vapor flow; it is expected to be greater at the higher temperatures.
4. (a) evaporation at the warm end. Lower moisture content is expected as the temperature of the layer inside the evaporating zone increases; this extends far from the warm plate, according to equation (13b).

   (b) condensation at the cold end. Higher moisture is expected near to the cold plate; the condensing zone extends far from the cold plate according to equation (14b).

An idea of the order of change in the value of p_o, p_o' and p_o'' in the conditions of the previous examples, is obtained from the data in the following table:

	as f (T)			as f (x)		
	13°C.	20°C.	28°C.	cold end	center	warm end
p_o (mmHg)	11.231	17.535	28.349	11.231	17.535	28.349
p_o'	0.735	1.087	1.652	1.102	1.630	2.478
p_o''	0.045	0.059	0.084	0.064	0.088	0.126

The influece of changes in p_s is given by the product of the rate of change of the vapor content of the air per unit distance times the velocity of the vapor flow. The amount of water condensed per unit time for a given section is:

$$(15) \qquad k \frac{dp_o}{dx} \frac{dq}{dt} = -kD \left(\frac{dp_o}{dx}\right)^2$$

where k is a conversion factor from mm. of Hg, to amount of vapor per unit air volume. Here also the value for D is not known.

The higher influence, however, may be expected at the ends of the column, since at each side (warm or cold) the changes in moisture content are of the same order as the total diffusing vapor. The other influences, on the contrary, involve only a relatively small part of this amount. The prevalence of the evaporation-condensation process over the influence of other diversions will depend largely on the relative length of the column and the distance of extension of the evaporating and condensing zones from the ends.

Now consider what happens in the liquid phase as a consequence of vapor flow.

As soon as evaporation starts at the warm side and condensation at the cold side, differences in soil moisture appear and difference in moisture tension may be built up. Liquid water therefore will move from the cold to the warm side, thus completing the circuit with the vapor phase.

This water flow in liquid phase obeys Darcy's law and is therefore dependent upon the value of the moisture conductivity at the varying moisture contents for each soil section. If the initial soil moisture, and consequently the hydraulic conductivity at each section is rather high, the water will flow back toward the warm end. If, however, the conductivity is low, or the flowing mass is large and requires a high tension gradient, the water will flow back only to a point where the evaporation is equal to the liquid flow and the circuit with the vapor phase will be closed. The portion beyond this wet front will stay at static equilibrium in a rather dry condition. The moisture content in this zone will satisfy the conditions that no vapor flow will occur, nor will any passage from the liquid to the vapor phase be found. This suggests a horizontal curve for the partial vapor pressure and an accompanying moisture content such that the corresponding tension satisfies equation (16) for the value of $\frac{p}{p_o}$ at all points.

If a point on the wet front having approximately 100% relative humidity at the water surface is considered, the next warmer layer evaporates less, due to its rapidly increasing moisture tension and the vapor pressure decreases

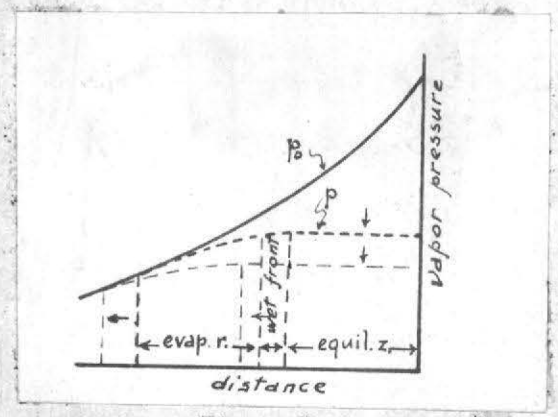

Fig. 6

Vapor pressure in the equilibrium zone

until at the warm end of the wet front the curve joins the equilibrium curve of the non evaporating zone. Since the relative humidity is given by the ratio of the value of such a curve to the original p_o - curve, and since the height of the horizontal curve will change with time, until stationary equilibrium is reached between the vapor and the liquid flow, the moisture content in the non evaporating zone will be related to the distance to the wet front. Thus a given point near the warm end, at stationary conditions, will be drier when the wet front is farther away.

Flow in an Interrupted Cylinder

Until now a continuous soil cylinder has been considered. Suppose the cylinder is broken into sections leaving between them an air space. This will interrupt the liquid flow, while permitting the vapor flow.

This scheme has often been applied, but no mention is found in the literature of the complications it implies.

First of all, when the column is broken a new surface is created. The total pore-space along this surface is the same as for the unbroken soil, and it is filled with the flowing vapor. The remaining part of the section area = (100-air filled porosity)%, is now free to evaporate, since it has become wet. Two components of the vapor flow in the air gap must therefore be combined. The mass of vapor coming out of the pores, after crossing this space will continue its flow through the pores of the next slice. The component given by the evaporation, on the contrary, must stop its flow as soon as it encounters the face of the next slice and it will therefore condense hereon. The water condensed at the warmer side of the cool slice, increases the soil moisture content at this point. At the colder side of the same slice, the moisture content is decreased by evaporation. A moisture gradient is thus built up and, if a tension gradient is also present, the moisture will flow in liquid phase in the same direction as the vapor: i.e. from warm to cold. Thus in a broken soil column a moisture transfer higher than in an unbroken column is expected. The magnitude of this excess flow will be discussed later.

Another complication of this case involves the thermal gradient. When dealing with a continuous column the thermal conditions can be kept constant and uniform throughout the soil. When dealing with alternate layers of soil and air, the thermal conductivity becomes a periodic function of the distance. In order to maintain a uniform heat flow, there must be the following relation between conductivity and the gradient:

$$(17) \qquad C_a \; T'_a = C_s \; T'_s \quad \text{or} \quad \frac{C_a}{C_s} = \frac{T'_s}{T'_a}$$

where C_a and C_s are the thermal conductivity of air and soil respectively, and $T' = \frac{dT}{dx}$ is the thermal gradient also in air or soil. The thermal gradient distribution in the cylinder will therefore be as shown in Fig. 7.

Suppose all of the soil slices are brought together at one side of the cylinder, leaving on the other side open air space equal to the sum of the previously separated air gaps. Since the extreme temperatures are fixed and also the average thermal gradient, and since here also equation (17) holds, the slope in each section will be the same as before, as shown in Fig. 7.

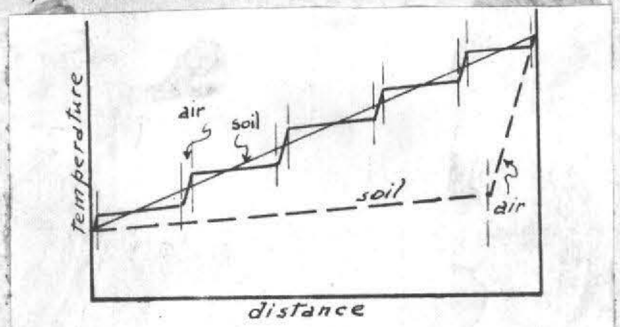

Fig. 7

Temperature gradients

If L is the length of the cylinder, T the difference of the temperature at the extremes, and $\frac{1}{n}$ is the relative proportion of the air space, then:

$$\text{(18a)} \qquad T'_a \frac{L}{n} + T'_s \frac{(n-1)\,L}{n} = \Delta T$$

and from (17):

$$\frac{T'_a L}{n} + \frac{T'_a C_a}{C_s} \; \frac{(n-1)\,L}{n} = \Delta T$$

$$\text{(18b)} \qquad T'_a = \frac{\Delta T}{L\left(\frac{1}{n} + \frac{C_a}{C_s} \; \frac{n-1}{n}\right)}$$

Considering ΔT, L; C_a, C_s as constants, let $n \to \infty$, (i.e. the thickness of the air layer tend to zero), the term

$(\frac{1}{n} + \frac{C_a\ (n - 1)}{C_s\ n})$ tends to $(o + \frac{C_a}{C_s})$ and

$$\lim_{n \to \infty} T'_a\ (n) = \frac{T}{L}\ \frac{C_s}{C_a}$$

also, since $\frac{C_a}{C_s} < 1$, T'_a (n) is an increasing function, for $n \to \infty$. This means that the thinner the air gap, the higher the temperature gradient in the air (but always less than the average gradient multiplied $\frac{C_s}{C_a}$).

If in (18b) $n \to 1$, i.e. the air space increases until no more soil is included in the cylinder, T'_a decreases and tends to $\frac{\Delta T}{L}$, the value for the average slope.

Note, however that (18b), while having a limit for $n \to \infty$, is undetermined at $n = \infty$. This means that as soon as the air layer disappears completely no slope at all exists in the air.

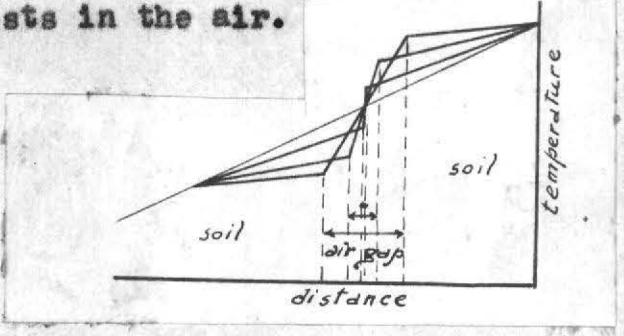

Fig. 8

Influence of the air gap thickness as the temperature gradient.

If in (18b) T'_a is expressed as f (T'_s) obtained from (17), we have:

(19)

$$T'_s = \frac{\Delta T}{L(\frac{1}{n}\frac{C_s}{C_a} + \frac{n - 1}{n})}$$

and for $n \to \infty$, T_s tends to $\frac{\Delta T}{L}$. This implies that the difference in temperature between the two faces limiting an air gap becomes smaller as the thickness of the air gap decreased (see fig. 8).

Now consider the interference to the moisture flow resulting from these alterations in the thermal conditions.

Since $p_s = f(T)$, there will be a different vapor pressure gradient in the air gap. Also the diffusivity and the quantity of vapor flow are different. Assume that for a small thickness of the air layer, $p = kT + C$, therefore we may write:

(20a) $$\frac{p_{at}'}{T_a'} \qquad \frac{p_s'}{T_s'}$$

where $p_{at}' = \frac{dp_{ar}}{dx}$, the vapor pressure gradient expected in the air layer, and $p_s' = \frac{dp_s}{dx}$ the vapor pressure gradient in the nearest layer of soil. From (20a) and (17) we have:

(20b) $$p_{at}' = \frac{p_s' T_a'}{T'_s} = p_s' \frac{C_s}{C_a}$$

Since there must be evaporation from the warmer face, and condensation on the cooler, the vapor pressure gradient in the air must be a little smaller in order to promote such evaporation and condensation. If p_a is the real vapor pressure in the air, at the mid point of the air gap $p_a = p_{at}$. The vapor flow in the air space now becomes:

(21a) $$\frac{dq}{dt} = A\, D_a\, p'_a$$

and also:

(21b) $$\frac{dq}{dt} = A\, D_s\, p'_s + E$$

where D_a and D_s are the diffusion coefficients for air and soil and E is the evaporation rate per unit time given by: $E = A\,K\,(p_o - p\quad)$ according to equation (12b). If d is the length of the air gap, from fig. 9 and from (20b)

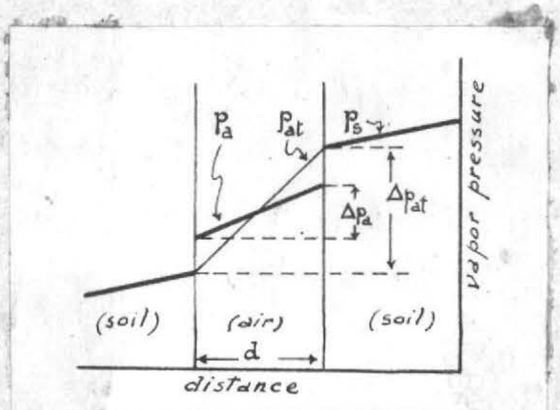

Fig. 9

Vapor pressure gradient in the air gap.

it develops that the difference in the theoretical vapor pressure between the cold and the warmer face is:

(22a) $$\Delta p_{at} = d\, p'_{at} = d\, p'_s \frac{C_s}{C_a}$$

similarly, the difference in the actual vapor pressure in the air is:

(22b) $$\Delta p_a = d\, p'_a$$

and from (22a) and (22b), the difference between p_{at} and p_a at the warm face, $(x = w)$ i.e. the value for (p - p) of equation (12b) is:

(23) $$p_o - p = p_{at}(w) - p_a(w) = \tfrac{1}{2}\left(d\, p'_s \frac{C_s}{C_a} - d\, p'_a\right) = \frac{d}{2}\left(p'_s \frac{C_s}{C_a} - p'_a\right)$$

Equating (21a) and (21b), substituting for E and using (23) we have:

(24a) $$p'_s D_s A + AK \frac{d}{2}\left(p'_s \frac{C_s}{C_a} - p'_a\right) = p'_a D_a A$$

or

(24b) $$\left(D_s + \frac{K\, C_s}{2\, C_a} d\right) p'_s = \left(D_a + \frac{K}{2} d\right) p'_a$$

since p'_s is function of d, it cannot be integrated.

By using (24b):

$$p'_a = p'_s \frac{D_s + \frac{KC_s}{2\,C_a} d}{D_a + \frac{K}{2} d}$$

for a small range of temperature, assuming $p'_s = T'_s\, k$, and applying equation (19) where now $d = \frac{L}{n}$:

$$(24c) \qquad p'_a = \frac{k \;\; T}{d\,(\frac{C_s}{C_a} - 1) + L} \left(\frac{D_s + \frac{KC_s}{2C_a} d}{D_a + \frac{K}{2}\; d} \right)$$

The actual vapor pressure gradient p'_a , for the limit cases of <u>d</u> assumes the following values:

$$\lim_{d \to o} p'_a = \frac{k\,\Delta T\, D_s}{D_a}$$ i.e., it tends to be independent of the thermal properties of the soil.

$$\lim_{d \to L} p'_a = \frac{k\,\Delta T\; C_a\; (D_s + \frac{K}{2}\frac{C_s}{C_a} L)}{LC_s\; (D_a + \frac{K}{2} L)}$$

This limit, however, does not represent the conditions of no soil and an evaporating free water surface at the end, since it requires that the warm end be porous and vapor diffuses through these pores.

For the difference between p_a and p_{at} at the evaporating surface $(x = w)$:

$$(25a)\; p_{at}(w) - p_a(w) = \frac{\Delta p_{at} - \Delta p_a}{2} = \frac{d}{2}(p'_{at} - p'_a) = \frac{d}{2}(p'_s\frac{C_s}{C_a} - p'_a)$$

and from (24c)

$$(25b)\quad p_{at}(w) - p_a(w) = \frac{K \;\; T}{2(\frac{C_s}{C_a} - 1 + \frac{L}{d})} \left(\frac{C_s}{C_a} - \frac{D_s \;\; \frac{KC_s}{2C_a} d}{D_a + \frac{K}{2} d} \right)$$

and:

$$\lim_{d \to 0} \left(p_{at}(w) - p_a(w) \right) = 0$$

$$\lim_{d \to 1} \left(p_{at}(w) - p_a(w) \right) = \frac{k \, \Delta T \, C_a}{2 \, C_s} \left(\frac{C_s}{C_a} - \frac{D_s + \frac{K \, C_s \, 1}{2 \, C_a}}{D_a + \frac{K1}{2}} \right)$$

It is evident that the thinner the air gap, the smaller the evaporation in the air gap.

Another important influence of the thermal gradient distribution on the moisture flow, is related to the conditions at the ends of the column. It has previously been shown how evaporation and condensation take place at the ends of a continuous column. When the saturation vapor pressure curve in a broken column is as shown in fig. 10 the vapor pressure curve in the evaporating region, and in the condensing region, will break at the end of the soil slice. Therefore the next soil slice will not be influenced by evaporation (or condensation) unless the vapor pressure curve in this region is low (or high) enough to join the saturation vapor pressure curve in the next layer. This will happen at the evaporation zone, when the moisture content is reduced below a limit where the evaporation rate becomes

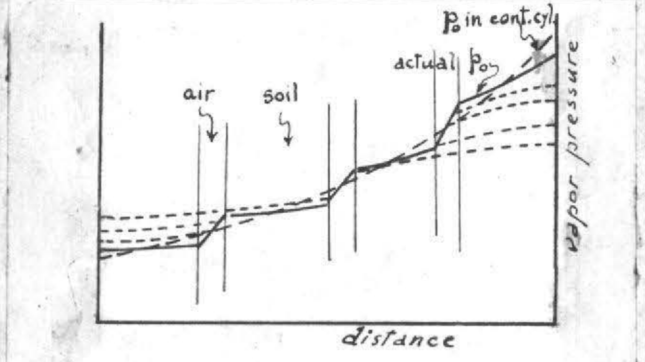

Fig.10

Influence of the air gap on the extension of evap. and cond. zones.

naturally influenced by the soil moisture tension. This is shown in fig. 10.

Since the thermal gradient influences both the slope of the vapor pressure in the soil and the difference of vapor pressure at the cold and warm face of the air gap, it may influence in two ways the extension of the evaporating and condensing region. First, if the difference of vapor pressure at the air-soil face is low (i.e. small air gap), the evaporation or condensation curve has a higher probability of extending into the next slice of soil. In this case the conditions are similar to the continuous column. If the air gap is large, the step in the vapor pressure curve along the air space is high and it is difficult for the evaporating or the condensing curve to extend across the air gap. However, since the surface involved in the processes of evaporation and condensation are now limited by the air-water interface of the terminal slices, the vapor pressure curve must be lower (or higher, respectively) than it would be in a continuous column.

It should be interesting to make some theoretical prediction on the relative importance of these alterations from the conditions of an unbroken column. Since equations (13b) and (14b) could not be solved and many soil characteristics are unknown, the prediction will wait for experimental results. In general it may be said that if a rather large air-water interface is required to be involved in the evaporation and condensation processes at the column ends, the evaporation and condensation phenomena in the air gaps is lowered.

MATERIAL AND METHODS

The soil used is a Millville silt loam. Its field capacity is 21% (approximately); its permanent wilting percentage is 7% (approximately). The air-dried soil was brought to the desired moisture content and then kept in a closed can. This soil was used for a large number of tests. Three different batches of moist soil were prepared. In order to wet the soil as uniformly as possible without disturbing its structure, the dry soil was let stay overnight at below freezing temperature. It was then thoroughly mixed ✓ ? with a weighed amount of fresh snow. The operation was performed at freezing temperature. Before use, the soil was let stay at least one week in the storage can. Two different moisture levels were used, about 17.5% and 9.5%. The method gave satisfactory uniformity of moisture while retaining structure.

Leucite cylinders were used as containers. They were ✓ ? 10 cm. long and 7.25 cm. in diameter. They were cut along two generatrixes. In part of them 5 thermistors were in- ✓ ? serted at 2 cm. intervals, beginning 1 cm. from one end. With these devices it was possible to record the temperature inside the soil sample at different points.

These cylinders were placed horizontally between two steel-plates forming the side of two water baths which were held at different temperatures. The high temperature (about

30°) was obtained by use of a common thermoregulator. A ✓ stirrer was used to bring about uniformity of the temperature in the bath. The low temperature was obtained by continuous ✓ flow of cold water at about 10° C. The constant temperature room was held at 20° C. There was a slight loss ✓ of temperature gradient along the bath walls. The thermal gradient inside the soil column was kept at about 1.5° C./cm., the observed values gave an average of 1.5 ± 0.1° C./cm. For the series with compact wet soil, the gradient happened to be about 1.7 ± 0.1° C./cm. Cylinders without thermistors were used only when the introduction of these in the soil was practically impossible. The temperature gradient inside the soil was kept uniform by coating the cylinders with a thick layer of insulating material. *insulation* The best results were obtained by a first layer of cotton, about 3 - 4 cm. thick ✓ when pressed, and an external layer of foam rubber. The latter was obtained by winding around the cylinders (a pair each time) a strip about 7 feet long and 7 mm. thick, of this foam rubber.

The soil was put in the containers either as a continuous ? column or in five slices separated by an air gap. Two different compactions were tested; in one series the total porosity of the soil mass was 49.9% db:1.32, and in the second series the total porosity was 34.9%. db:1.72

The low compaction was obtained for the continuous ? cylinders by a standard procedure, consisting of slightly tapping the soil at each 1 cm. layer and then destroying the flat surface formed, before adding the new layer. The high compaction was similarly obtained by heavier tapping.

A certain difficulty was found in forming the air spaces in the broken columns. First the use of wire gauzes was tried. Two different gauze types were tested, one a 40 mesh brass gauze, having a net empty space, calculated as a projection on a flat surface equal to 36.0%. The other coarser screen was obtained from an originally 14 meshes galvanized iron gauze; its wires were then tilted until forming an angle of 60° (instead of the initial 90° angle). Its net empty space was then 49.2%.

Since the use of the wire screens proved unsatisfactory, attempts were made to eliminate their use. This was rather easy when compact wet soil was used. A measured amount of this soil was put in a short leucite cylinder about 2.5 cm. long and was compacted in the same way as for the continuous more compact soil column. This rather compact cake was then taken out of the small cylinder and placed in a long cylinder together with other similar slices. When dealing with dryer soils, in order to have a good consistency and also to obtain a comparable structure, the cakes were first made with wet soil (18% moisture) and were then allowed to dry to the desired moisture.

With the loose wet soil the slices were prepared directly in the long cylinder. After slightly compressing a certain amount of soil, a leucite disc, 3 mm. thick, was interposed before adding new soil. Four of such leucite diaphragms were set at about 2 cm. distance from one another or from the column ends. After the operation was finished, the cylinder was opened on the side and the diaphragms were removed with much care.

When compact cakes were placed in the cylinders, a layer of stopcock-grease was spread on the cylinder wall in order to obtain good contact with the soil and to prevent any vapor flow around the plastic wall.

When dry continuous columns were tested, they were prepared first as single isolated cakes of wet soil. Then, after the proper moisture content was obtained, these slices were connected together after scratching the surface, and the whole column was again compressed in order to have good connection between the slices. This was done in order to have a soil comparable not only in moisture content but also in structure, with the broken column.

An important point was to obtain approximately the same compaction in every test with both broken and unbroken columns. With a little practice this was obtained to a good approximation. This was checked by weighing the leucite containers before and after being filled with soil slices. When continuous columns were tested, the required amount of soil was first weighed and then it was put in the cylinder. Only small differences from the calculated amount of soil, were observed. The amount of soil to be put in the continuous cylinders was calculated from that required to prepare the broken columns, and assuming an average air-layer thickness of 2.5 mm.

The distance between the soil slices was changed in a series of tests in order to observe its influence on the moisture flow; the range tested was from about 1 mm. to about 10 mm. When not explicitly mentioned, the thickness of the air gap without gauzes is to be considered about 2.5 mm. When wire screens were used the diaphragm was about 2.3 mm. thick.

Two greased rubber rings permitted a tight connection at the edges of the cylinders. The longitudinal fissures along the cylinder wall were sealed with wax in order to prevent any vapor losses. Only a small hole was left in order to maintain an overall pressure equal to the atmospheric pressure.

As a general rule two tests were run at the same time, keeping the cylinders side by side. With few exceptions each continuous soil test was run parallel with the broken column test. By this way the error between the pairs was reduced.

The tests were run for variable periods of 6 hours, 12 hours, 1, 2, 3, 4, and 7 days.

At the end of each test the cylinders were opened on the side and samples were taken for moisture determinations. Fifteen samples were taken from each cylinder; 3 from each slice when the column was broken. All samples were cut along planes perpendicular to the cylinder axis. For two tests the samples have been taken separately from the upper and lower half of each cylinder; in these cases only 10 samples were taken along the axis, making 20 samples per cylinder. Each sample weighed about 15-25 grams.

The moisture content was determined by drying at 105° - 110° C. for about 17 hours.

The results are shown in tables 1 to 8 and figures 1 to 9.

RESULTS

Continuous Columns.

Table 1 and fig. 11 show clearly the influence of the temperature gradient on the moisture displacement in a continuous soil column, at a moisture content slightly below the field capacity. The effect is evident after 6 hours. The change in the moisture distribution continues at a near constant rate until the third or fourth day. After this time the moisture curve assumes a constant pattern, it does not exceed 24% moisture content at the cold end. This is slightly wetter than the field capacity for this soil. The curve, from the cold plate decreases slowly until a point where it decreases rapidly producing a steep moisture gradient. This region is called the wet front. The moisture of the remaining warmer drier part does not decrease below 4.4%. This figure is much lower than the wilting coefficient for this soil.

Comparing the data of table 2 and figure 12 with the former, shows the importance of the compaction. Here also the moisture distribution curve changes with time, but the equilibrium is reached sooner. After two days the curve is stabilized. The curve has a more uniform gradient than the curve for the loose soil. Its slope is steeper than the first portion (cold) of the corresponding curve for the loose soil. It reaches the warm side without reaching the

Table 1. Moisture distribution in continuous loose soil columns (17.5% moisture) *

No. of sample	Approx. distance from cold face (mm)	After											
		6 hours		12 hours		1 day		2 days		4 days		7 days	
		Moisture %	Temp. °C.	M. %	T. °C.	M. %	T. °C.	M. %	T. °C.	M. %	T. °C.	M. %	T. °C.
1	1-7	19.7	-	22.6	-	22.3	-	22.9	-	23.6	-	23.8	-
2	7-14	18.7	14.0	20.6	14.0	21.3	15.0	22.2	15.0	23.3	15.0	23.3	14.5
3	14-20	18.1	-	19.2	-	20.4	-	22.1	-	23.0	-	23.0	-
4	20-27	17.6	-	18.0	-	19.6	-	22.0	-	23.2	-	22.9	-
5	27-34	17.5	18.4	17.8	18.0	19.1	17.6	21.7	18.4	23.0	19.2	22.8	17.5
6	34-40	17.6	-	17.7	-	18.8	-	21.6	-	22.8	-	22.5	-
7	40-47	17.4	-	17.7	-	18.4	-	21.0	-	22.3	-	22.1	-
8	47-54	17.5	20.6	17.6	20.0	18.4	20.0	20.3	20.6	22.1	21.5	21.9	19.9
9	54-60	17.6	-	17.9	-	18.2	-	19.9	-	21.4	-	21.4	-
10	60-67	17.5	-	17.8	-	17.8	-	18.3	-	18.8	-	18.8	-
11	67-74	17.7	22.2	17.7	22.3	17.1	22.8	15.9	23.1	12.2	24.1	12.4	22.0
12	74-80	17.7	-	17.8	-	16.6	-	13.1	-	7.9	-	7.5	-
13	80-87	17.3	-	16.7	-	15.0	-	8.9	-	6.0	-	5.5	-
14	87-94	16.4	27.0	14.5	25.1	12.4	25.2	6.5	26.2	4.5	27.0	4.4	26.5
15	94-100	13.4	-	9.6	-	8.6	-	5.4	-	4.5	-	4.2	-

* Temperature figures are means for values observed during the experiment.

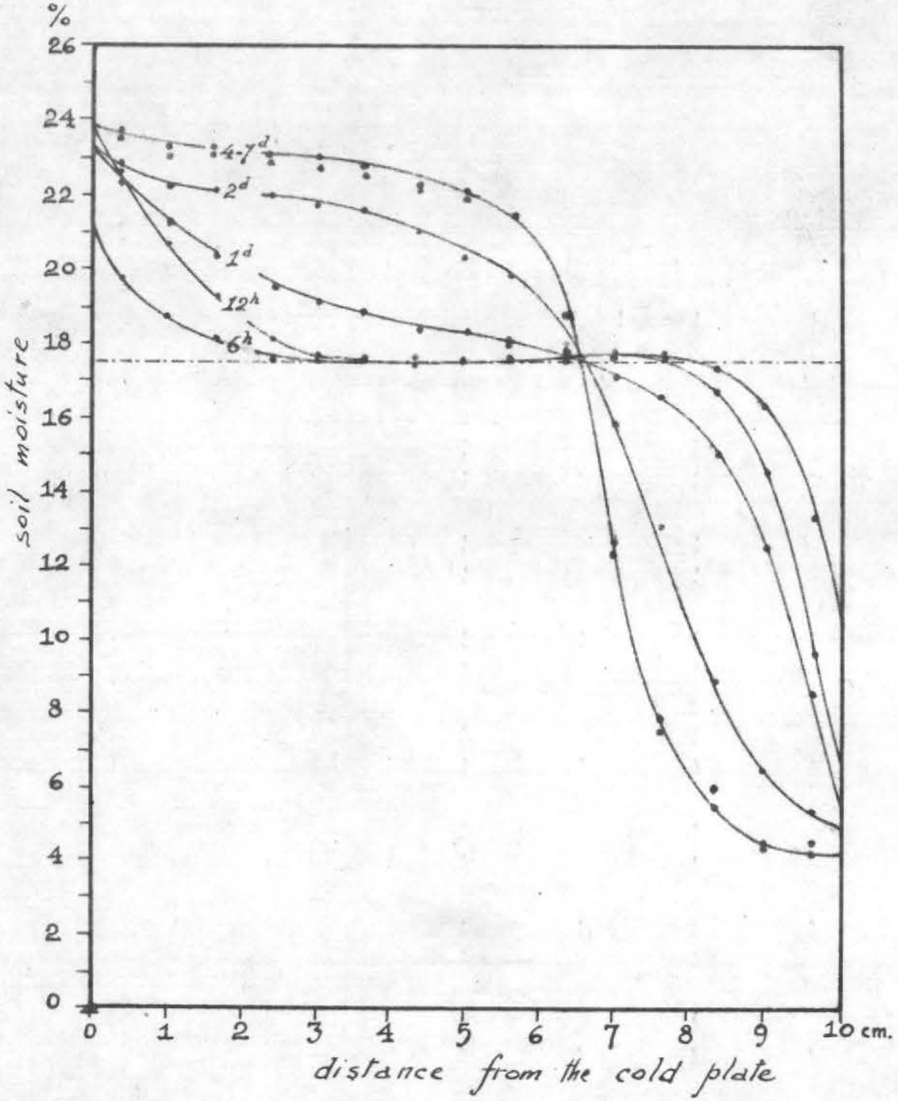

Fig. 11. Moisture distribution in continuous loose soil columns.

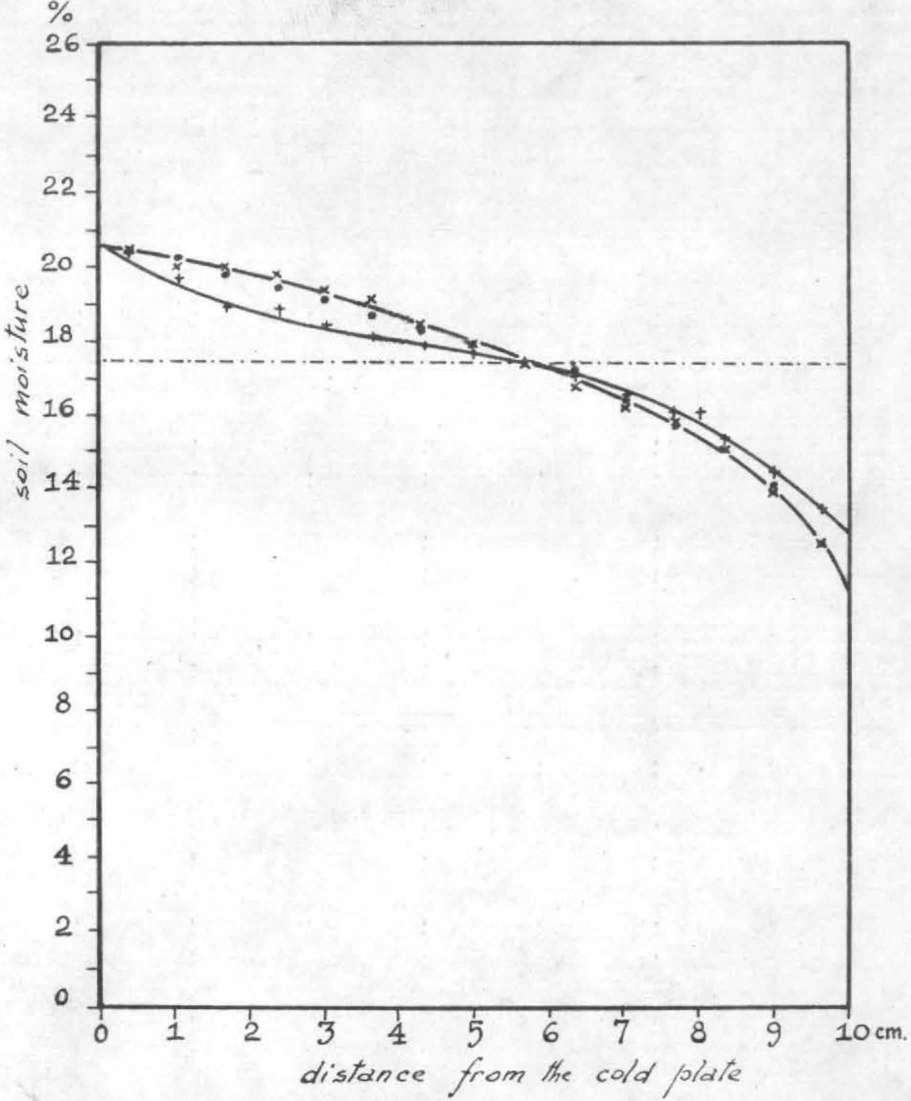

Fig. 12. Moisture distribution in continuous compact soil columns.

Table 2. Moisture distribution in continuous compact soil columns (17.5% moisture)

Number of sample	Approx. distance from cold face (mm)	Soil moisture distribution (%) after: 1 day	2 days	4 days
1	1-7	20.3	20.4	20.4
2	7-14	19.7	20.0	20.3
3	14-20	18.9	20.0	19.8
4	20-27	18.9	19.8	19.4
5	27-34	18.5	19.4	19.1
6	34-40	18.2	19.1	18.7
7	40-47	17.9	18.4	18.4
8	47-54	17.7	17.9	17.9
9	54-60	17.5	17.4	17.4
10	60-67	17.0	16.7	17.2
11	67-74	16.5	16.1	16.4
12	74-80	16.0	15.8	15.7
13	80-87	15.3	15.0	15.0
14	87-94	14.4	13.8	14.0
15	94-100	13.4	12.4	12.4

5/6 ; 5/6

(*) for data obtained after 3 days see Table 7.

lower limit of drying. There is no flex point.

The experimental data for the 9.6% moist soil column, (fig. 16, table 8) show a large deviation from the curve; this evidently results from the fact that the column was built up from single slices. The curve shows a steep slope at the cold face, and gradually changes to almost a straight line with a smaller slope at the warm face.

Broken Columns.

Table 3 and figure 13 show the influence of the screens. It is notable that there was an accumulation of water at the cold column-end and a depletion at the warmest slice. When the warmest slice had decreased to about 8% moisture, the next slice began to lose its moisture much more rapidly Inside each slice having a moisture higher than about 14%, it is evident that moisture accumulated against the screen. The impediment given by the screen is also evident from the fact that the moisture in the warmer slices (except the actively evaporating one) is higher than the moisture of the colder (except the coldest). This brings about an inversion in the sign of the moisture gradient between slices.

The coarser screen shows the same effects but less pronounced.

Table 4 and figure 14 show the results obtained after elimination of the screens. Here both the moisture distribution inside each slice and that between the slices has exactly opposite direction than when screens are used. Some irregularity in the slope of the second slice (from the

Table 3. Moisture distribution in loose soil columns broken by use of wire screens (moisture 17.5%)

No. of sample	Approx. distance from cold face (mm)	After 6 hours Moisture %	6 hours Temp. °C.	12 hours M. %	12 hours T. °C.	2 days M. %	2 days T. °C.	4 days M. %	4 days T. °C.	7 days M. %	7 days T. °C.	2 days* Moisture %
1	1-7	21.6	-	22.6	-	26.4	-	33.4	-	44.3	-	27.5
2	7-14	19.6	13.6	20.6	14.0	25.6	14.9	33.2	13.5	43.2	13.3	27.3
3	14-20	18.5	-	16.3	-	25.4	-	29.8	-	43.5	-	27.9
4	20-27	19.0	-	18.4	-	17.8	-	18.4	-	16.8	-	19.1
5	27-34	18.4	17.6	17.4	17.7	16.3	18.3	18.1	18.6	15.2	17.2	18.8
6	34-40	17.7	-	17.0	-	16.6	-	16.8	-	15.1	-	17.8
7	40-47	19.1	-	19.0	-	19.1	-	18.1	-	15.3	-	18.1
8	47-54	18.4	21.1	17.8	20.6	18.2	21.2	17.9	22.2	15.0	20.3	17.4
9	54-60	18.1	-	16.3	-	16.3	-	15.7	-	12.1	-	16.3
10	60-67	19.5	-	19.6	-	20.1	-	15.1	-	9.4	-	18.1
11	67-74	18.9	24.4	18.8	23.0	19.9	23.7	15.2	25.3	7.7	23.0	18.5
12	74-80	18.3	-	17.7	-	18.1	-	11.3	-	6.6	-	16.3
13	80-87	17.9	-	17.9	-	8.6	-	5.5	-	4.4	-	7.5
14	87-94	17.2	27.8	14.6	25.5	7.0	26.4	4.9	26.2	4.0	26.7	6.5
15	94-100	13.9	-	9.4	-	5.8	-	4.5	-	3.7	-	5.3

* The figures of the last column were obtained after using the coarser gauze.

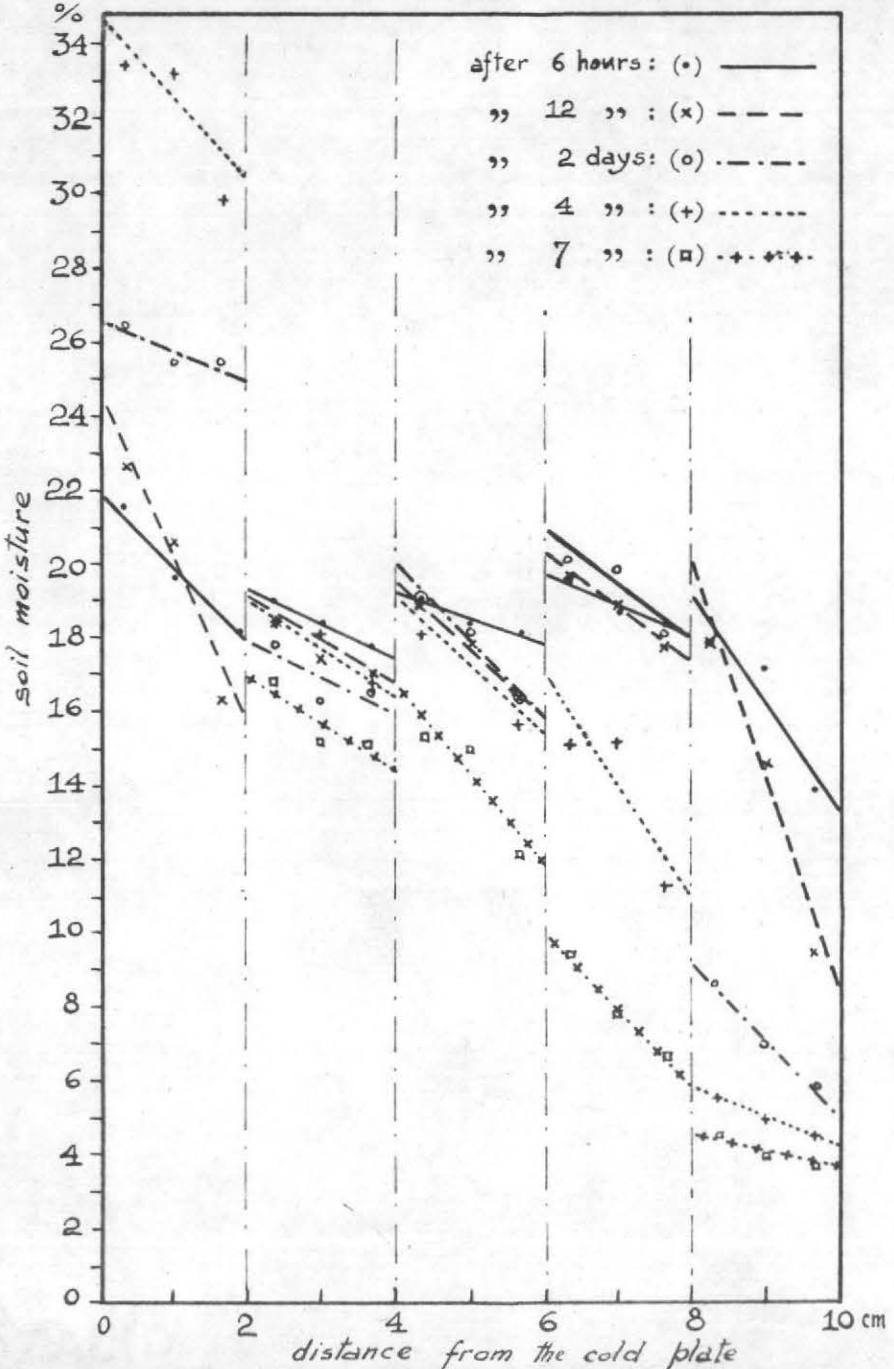

Fig. 13. Moisture distribution in loose soil columns broken by screens.

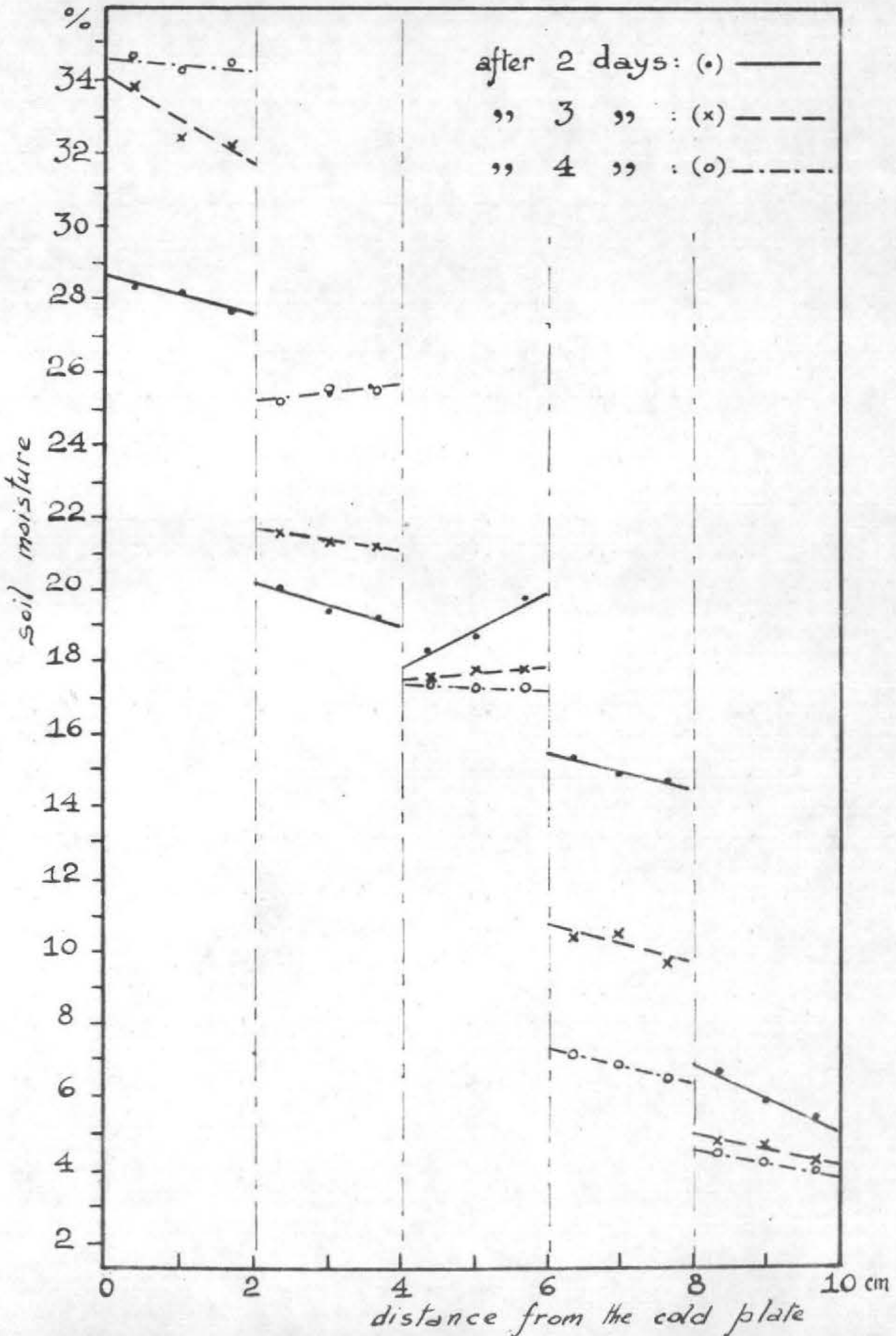

Fig. 14. Moisture distribution in loose soil columns broken by air gap.

Table 4. Moisture distribution in loose soil columns broken only by air gaps (17.5% moisture)

Number of sample	Approx. distance from cold face (mm.)	Soil moisture distribution (%) after:		
		1 day	2 days	4 days
1	1-7	28.3	33.8	35.6
2	7-14	28.1	32.4	35.3
3	14-20	27.6	32.2	35.4
4	20-27	20.0	21.5	22.2
5	27-34	19.4	21.3	25.5
6	34-40	19.2	21.2	25.4
7	40-47	18.3	17.5	17.4
8	47-54	18.7	17.8	17.3
9	54-60	19.8	17.8	17.3
10	60-67	15.4	10.4	7.2
11	67-74	14.9	10.5	6.9
12	74-80	14.8	9.6	6.5
13	80-87	6.7	4.8	4.5
14	87-94	5.9	4.7	4.3
15	94-100	5.5	4.2	4.0

cold side) results from occasional contact between slices.

The water accumulates at a higher rate to the cold end. The moisture gradient inside the coldest slice shows great variation. This is probably due to the fact the sampling of this almost saturated soil, involved a certain puddling effect.

The same type of responses is given by the compact soil slices at 17.5% moisture (table 5, figure 15). The slope inside the slices is also from warm to cold. The slope between slices and the behaviour of the extreme slices is similar to that of the former case.

The same response is given by the 9.6% moist soil (figure 16, table 8). Here the slope inside slices is higher. The slope between slices is about the same as in the continuous column.

If we plot the accumulation at the colder face against time for the three cases of screened loose soil, unscreened loose soil, or unscreened compact soil, we have a straight line curve (see figure 18). At the same temperature gradient, the accumulation when screens were used is about 20.8% less than without screens. The higher accumulation in the compact soil seems to be accounted for by the slightly higher thermal gradient.

Figure 17 and table 6 show the influence of the distance between slices. It is evident the rapid change in moisture distribution between the slices as soon as the distance decreases below 5 mm. The warmer slices, provided they have not reached the minimum moisture value, tend to

Table 5. Moisture distribution in compact soil columns broken by air gaps (17.5% moisture)

Number of sample	Approx. distance from cold face (mm)	Soil moisture distribution (%) after:			
		1 day	2 days	3 days	4 days
1	1-7	25.5	29.2	34.5	42.7
2	7-14	22.6	29.1	34.5	42.2
3	14-20	23.3	29.1	34.1	42.7
4	20-27	18.0	20.7	20.7	18.8
5	27-34	18.0	21.2	21.0	19.1
6	34-40	18.7	21.5	21.6	19.8
7	40-47	17.8	18.4	18.1	14.5
8	47-54	17.9	18.5	19.0	14.4
9	54-60	18.4	19.0	19.5	14.7
10	60-67	17.2	13.3	8.7	6.8
11	67-74	17.5	13.1	9.2	6.8
12	74-80	18.1	13.1	8.9	6.7
13	80-87	10.1	5.6	4.5	4.9
14	87-94	10.1	5.3	4.5	4.7
15	94-100	9.9	4.9	4.2	4.5

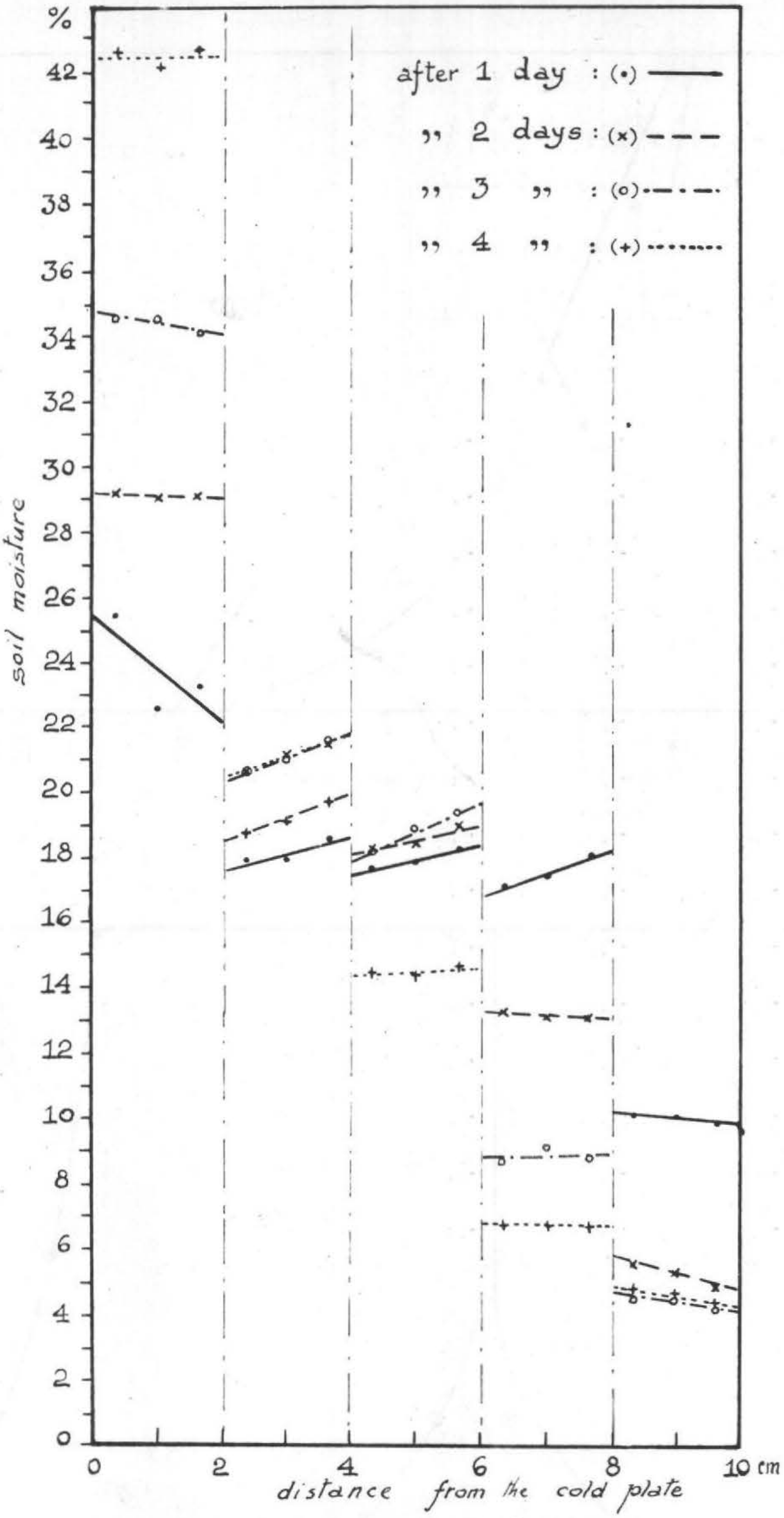

Fig. 15. Moisture distribution in compact soil columns broken by air gaps.

Table 6. Influence of the air gap thickness on the moisture transfer (moisture distribution for compact soil at 17.5% moisture) (after 3 days)

Number of sample	Approx. distance from cold face (mm)	Air gap thickness			
		1 mm	2.5 mm	5 mm	10 mm
1	1-7	36.0	34.5	33.8	32.1
2	7-14	36.5	34.5	32.0	31.5
3	14-20	36.5	34.1	33.2	31.0
4	20-27	23.7	20.7	18.5	20.7
5	27-34	23.2	21.0	18.4	20.5
6	34-40	23.4	21.6	18.1	20.9
7	40-47	14.4	18.1	19.3	19.5
8	47-54	14.5	19.0	19.4	19.4
9	54-60	15.1	19.5	18.8	19.5
10	60-67	7.7	8.3	11.4	11.3
11	67-74	8.2	9.2	11.4	11.1
12	74-80	8.3	9.3	11.5	10.8
13	80-87	5.5	4.5	5.3	4.6
14	87-94	4.5	4.5	5.0	4.5
15	94-100	4.7	4.2	4.9	4.2

Table 7. Difference in moisture distribution between upper and lower part of continuous soil columns (17.5% moisture)
(after 2 days)

Number of sample	Approx. distance from cold face (cm)	Loose soil upper part	Loose soil lower part	Compact soil upper part	Compact soil lower part
1	0-1	23.0	23.1	20.1	20.5
2	1-2	22.6	22.5	19.7	19.9
3	2-3	22.2	22.4	19.3	19.4
4	3-4	21.9	22.0	18.6	18.9
5	4-5	20.7	21.3	18.2	18.1
6	5-6	19.9	20.0	16.9	17.2
7	6-7	17.4	17.4	16.0	16.6
8	7-8	13.0	12.9	15.4	15.4
9	8-9	8.4	7.7	14.6	13.8
10	9-10	5.8	6.0	13.8	14.2
-	average	17.59	17.63	17.26	17.40

Table 8. Moisture distribution for compact soil (9.6% moisture)

(after 3 days)

Number of sample	Approx. distance from cold face (mm)	broken column	unbroken column
1	1-7	19.8	17.6
2	7-14	19.2	15.0
3	14-20	18.1	12.6
4	20-27	9.4	11.4
5	27-34	10.1	11.0
6	34-40	10.4	9.6
7	40-47	7.8	9.6
8	47-54	8.4	9.0
9	54-60	9.0	8.7
10	60-67	5.9	8.6
11	67-74	6.1	7.4
12	74-80	6.1	6.2
13	80-87	4.8	6.3
14	87-94	4.9	5.7
15	94-100	4.3	5.2

decrease in moisture; the colder slices tend to increase in it.

In almost all cases the minimum moisture content to which the soil dries at the warm end is lower as the distance to the wet front increases. This holds for continuous as well as for broken columns.

Table 7 shows that no significant difference exists between the lower and the upper part of each soil section, for both compact and loose continuous columns.

DISCUSSION

First consider the evidence of the important role of the vapor flow in soil moisture transfer under a thermal gradient.

From the data of table 7, it is evident, as predicted from theory, that convection plays very little if any role in vapor flow. The small differences found between upper and lower layers are not significant.

Consider now the influence of the screens.

When a broken soil column has been used to interrupt the liquid flow by other researchers a double wire gauze screen was always interposed between two soil portions. In this condition an important role is played by the relative empty area of the screen. If this area is less than the porosity of the soil, the vapor flow will be impeded and vapor will condense behind the screen, and a smaller amount of vapor will cross the air gap than with an unbroken column. If the net empty area of the screen is higher than the porosity of the soil, the excess area (over the porosity of the soil) will increase evaporation, as previously mentioned, and the data on moisture transfer will be more or less biased. Also when a wire is in contact with the wet soil, the soil pores which are against the wire, do not have in front of them other pores, and the probability that some pores will be sealed off by the flat profile of the wire is increased (see fig. 21). This is evident if one thinks that the pores between the wire surface and the soil particles along the section A-B are comparable to one-half of the volume of the pore along the line C-D and therefore, their average diameter is smaller. It is not known, however, to what extent these arguments may have influenced the results of the other writers. The thickness of the screen is more likely to influence the vapor flow. The influence of the supplementary evaporation when a coarser screen is used, depends largely on the rate of evaporation per unit time and unit surface. If this evaporation rate is high, it will increase the bias when coarse screens are used, but it will decrease the effect of the sealing off the pores by the wires. Indeed, if a pore is sealed with water, vapor will condense on this filled pore, but it will evaporate from the surface of the wet soil particle exposed to the air between the wires. In such a case the only important fact should be the net empty area of the gauze. If, however, the evaporation rate is very small, both a small net empty area of the gauze and the sealing off effect are expected to be effective.

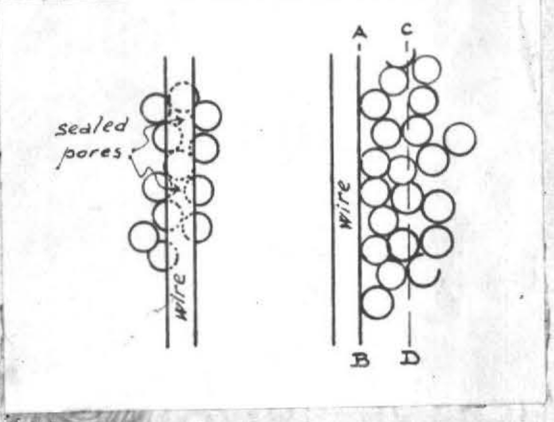

Fig. 21
Influence of the screens on the vapor flow.

In the work of Smith (1943), the vapor was expected to condense on the flat cold surface beyond the screen. In this case two other factors are involved in the moisture flow. First the screen is near the cold end and therefore it may happen that the slope of the supersaturated vapor curve is low so that little diffusion occurs. This will be the case if the condensation rate per unit area is low, so that the air-water interface involved is larger than that of the flat cold plate. The vapor should then condense in the soil, behind the screen. Also, it is to be observed that the condensation on a flat non-wetted surface, particularly if its attraction for the water is low, will be more difficult than on the concave menisci of the soil mass. When the condensation on the cold plate is started the water will be present in form of droplets with a convex surface, while condensation on a flat surface requires a higher vapor pressure. However, this last factor seems less important because of the small diameter of the soil pores and of the droplets involved. If the evaporation rate is low, it could become the only serious factor.

Looking at the results given in fig. 18, it is evident that the rate of moisture accumulation at the cold end is 3.8%/day when screens were used, against 4.8%/day when no screen was interposed. Note that the only point obtained for the coarser screen test is close to the line for no screen tests. The decrease of 20.8% of this slope due to the screens show that they have a real influence particularly when the wires are thick, but they still permit, at least in the conditions of this experiment, the detection of the vapor flow. In our cases the net empty space of the screens was still more reduced by a ring of wax used to get a good connection between screens and the lucite wall. This ring happened to be larger for the thicker gauze. A consideration of the small difference between the coarser gauze to the no gauze test, an indication of the small influence of the evaporation compoent in the vapor flow through the air gap, is bad.

Considering fig. 11, it is interesting to observe that in the first 12 hours, when the moisture transfer has materially affected only the extreme layers, the horizontal part of both the 6" and 12" curves show a tendency to increase from cold to warm. All the experimental points, but one, fit pretty close to the curve. Although this evidence is not conclusive it suggests that it could represent the influence of the variation in the vapor pressure curve as function of the distance in accordance with the predictions. In any case, those effects are too small to be considered in practice and in no other case were the effects apparent.

On the contrary, the evaporation and condensation effect is very evident. Looking at the graphs for the broken column, it is evident that condensation occurs not only on the coldest slice (even if it is here much larger), but also on the next less cold slice. Fig. 17 shows the influence of the air gap distance on this process. When this distance decreases below 5 mm., the moisture transfer increases and the second layer in condensation and the third layer in evaporation become active. This spreading of the evaporating and condensing region when the air gap is reduced was predicted. As the air gap between slices becomes narrower the difference in vapor pressure between soil and air regions along the warmer face of an air gap becomes smaller. This means that the evaporation is also smaller. Because of the small evaporating area at the slice surface, compared with the large area involved at the column ends which is available to supply vapor through evaporation, for the diffusion process, the diffusion component itself is far the most important in determining the vapor flow crossing the air gap. Therefore any factor influencing the diffusion, will likewise influence the vapor flow.

When we increase the thickness of the air layer, according to equation (19), the vapor pressure gradient decreases in the soil (slices) and therefore the diffusion rate decreases. Combining this fact with what has been said about evaporation, we may state that fig. 6 shows more exactly a decrease of flow due to decreased diffusion rate when the distance increases, rather than an increase of flow due to evaporation when the distance decreases. The rapid change between 0 and 5 mm. distance is then predictable from equation (19).

We have inferred that the amount of evaporation and condensation in the air layer is small. It is, however, not negligible. Its presence is manifested by the formation of a moisture gradient inside each slice (except the end slices), showing condensation at the warmer face and evaporation at the colder face of the soil slices.

The relationship between the observed moisture gradients and the liquid water flow is difficult to determine.

It is known that under field conditions a rather exact relationship between water tension and moisture content of the soil is reached at some time after an irrigation or rainfall. Many writers--Haines (1930), Richards (1931), Schofield (1938), etc.--have presented arguments and data indicating the existence of two curves, a wetting curve and a drying curve. Some writers claim that these curves do not represent true equilibrium curves, and argue that with sufficient time only one curve should be obtained.

Compare the equilibrium curve of fig. 12, for example, with the corresponding curves of fig. 15 for the broken columns. Since the permeability constant of Darcy's equation is a function of the moisture content, a point on the curve for the continuous column about in the middle may be chosen, and compared with a point on the middle layer of the broken column. These points have approximately the same moisture content. The slopes of the curves at this point are almost equal in magnitude but opposite in sign. This means that, if both moisture gradients correspond to a unique moisture retention curve, the liquid flor in both cases is of equal magnitude. The liquid flow in the continuous column at each point is equal and opposite to the vapor flow at that point. Since middle sections unaffected by evaporation or condensation have been chosen, the vapor flow in the continuous column is practically equal to the vapor flow in the unbroken column. The consequence is that in the broken column the evaporation component crossing the air gap should be equal to the diffusion component. But it has already been established that this is not the case; therefore the two moisture gradients for the broken and unbroken columns can not correspond to the same moisture retention curve. This re-emphasized the existence of two distinct stable moisture retention curves.

For the Millville silt loam a complete drying curve is available. A partial drying and wetting curve has also been calculated by Richards (1931) and a complete curve in terms of pF is reported by Baver (1948), Haynes (1930), and Richards (1931). They have shown that all points in the region bounded by the wetting and drying curves may be reached when the moisture is made to change in a certain way. In general the tension tends to shift smoothly from the initial value up to one on the drying curve if the soil is drying, and vice versa.

In our case, if we consider the equilibrium curve of the continuous soil, we have to neglect the portion of this curve at moisture values below the wilting point since it does not materially contribute to the flow. The remaining active part may be divided into a colder section where an increasing condensation may occur, and a warmer evaporating portion. The points at the cold face are certainly intensively wetting and their tension is expected to be on the wetting curve. Similarly, at the warmest evaporating section the tension is expected to be on the drying curve. Since the moisture tension curve in the soil must be continuous and since in the middle section there is no reason for the tension to be at either of the limiting tension curves, it is reasonable to expect that the tension at this point is intermediate. We cannot infer the position of the intermediate points. However, if the moisture characteristics curves are observed, it is apparent that at the higher moisture contents of the soil the drying and wetting curves become closer together (at least in the range from field capacity to about the wilting point). Since in our case the wettest point is about 24% (loose soil) or 20.5% (compact soil) moisture, and the warmest is about 8% and 12% respectively, we may assume that there is little error in the tension gradients if we draw for our case a tension curve like that shown in fig. 22a.

On the other hand, the curves inside the slices of the broken columns are more complicated since two distinct processes are superimposed. The second slice in fig. 15 is subjected to an overall condensation but the two faces of this slice are relatively evaporating or condensing. For this slice the first process is predominant during the first two days. During this time this curve cannot have points on the drying curve. It is not known if all its points are on the wetting curve, however. If this last was the case, due to the small moisture difference practically no liquid flow could occur since no gradient would exist, and the difference in moisture should represent about half the amount evaporated at one side. The difference in slope of the slices of fig. 16 can be interpreted as being due to either a higher tension gradient that is required for the liquid flow, or a little higher amount of evaporation occurring which compensates for the smaller diffusion rate (this depends on a higher tension at this moisture level). In any case, the moisture tension gradient must be low here, since the amount of flow inside the slices is expected to be rather small.

It is worthwhile to use these arguments and the experimental data to compute some of the soil constants. The liquid flow is dominated by the value of the hydraulic conductivity. From Darcy's equation we have:

$$\frac{dq}{dt} = AK\frac{d\psi}{dx} \quad \text{and} \quad K = \frac{\frac{dq}{dt}}{A\frac{d\psi}{dx}}$$

$A = 34.38\ \text{cm}^2$. The tension gradient may be obtained by considering that:

$$\frac{d\psi}{dx} = \frac{d\psi}{dM}\,\frac{dM}{dx}$$

where $M \equiv$ moisture percentage. The first factor of the right number is obtained from the moisture retention curve; the second factor is obtained from figs. 11 and 12 for the continuous column. The evaluation of $\frac{dq}{dt}$ is more complicated. If we consider a middle section, just half way between the condensing and evaporating region, practically no divergence in

Fig. 22a. and 22b. Moisture retention curve for the Millville silt loam.

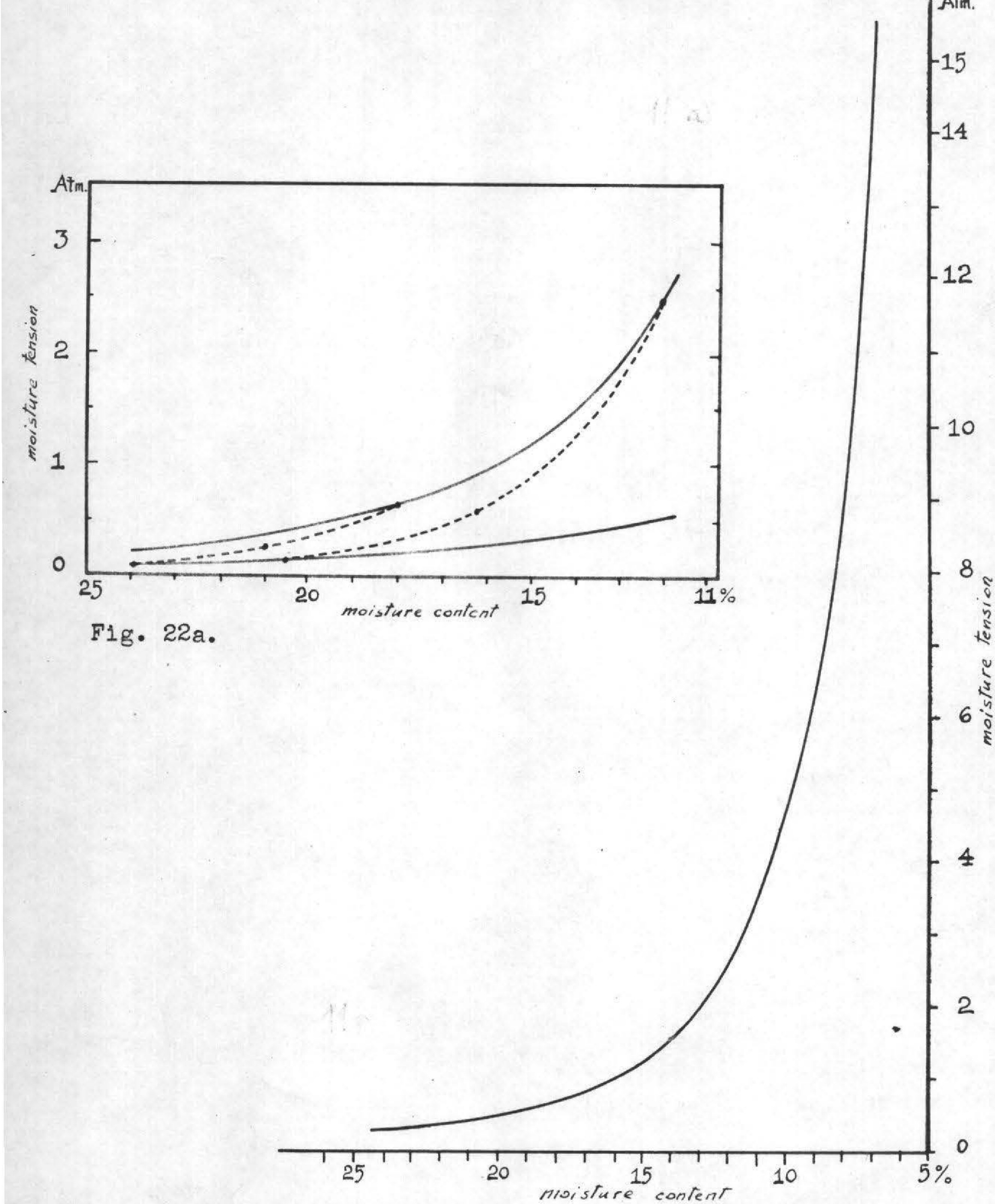

Fig. 22a.

Fig. 22b.

the flow will occur. For this case the rate of flow is equal to the summation of the rate of accumulation in the colder layers. For the compact soil, it is possible to use fig. 17 by extrapolating to zero air gap distance for the accumulation figures. In order to compute K for points to the left or right of the center, provided the moisture at this point is enough to insure vapor flow, it is necessary to know the value of the flow at this particular point. This computation cannot be exactly done. Fig. 19 has been obtained by taking for rate of accumulation at the coldest slice, the slope of the curve in fig. 18 when corrected for the air gap distance. For the second slice the rate of accumulation has been taken from the average accumulation in the first three days, since after this time this slice also started to evaporate. It is not possible to get exact data for the warm side since here the evaporating region is moving; however, it seems reasonable to assume as a first approximation, that the rate of depletion at the warm side should follow a symmetrical curve with respect to the condensing curve. This assumption seems to be supported both by the identity of equations 13c and 14c, and by the observation of the rate of depletion at the warmest layer during the first day compared to the average accumulation rate for the coldest layer. Fig. 9 is very interesting since it seems to prove that the evaporation and condensation regions not only extend far from the ends of the column, but even touch each other at a mid point. On the above basis the following figures have been computed for the moisture conductivity.

$K' = \frac{\eta}{g\rho\, 3600} K = .2834 K/\mu^2$

Table 9. Hydraulic conductivity values

soil column	distance from cold end (cm)	moisture %	tension Atm.	$\frac{dq}{dt}$ g/day	$\frac{dM}{dx}$ %/cm	$\frac{d\psi}{dx}$ Atm/cm	$\frac{d\psi}{dM}$ Atm/%	K $\frac{\text{cm/hour}}{\text{cm } H_2O/\text{cm}}$	K' intrinsic permeability μ^2
loose 17.5%	3.5	23.0	0.13	2.48	0.27	0.0109	0.041	23.2×10^{-5}	6.8×10^{-5}
compact 17.5%	2.0	15.0	0.90	4.24	1.20	0.3816	0.318	1.13×10^{-5}	$.33 \times 10^{-5}$
compact 17.5%	5.0	17.1	0.44	5.79	0.76	0.0980	0.129	6.04×10^{-5}	1.78×10^{-5}
compact 17.5%	8.0	19.6	0.20	4.24	0.44	0.0237	0.054	18.38×10^{-5}	5.4×10^{-5}

These figures are of the order of magnitude expected from the data found in the literature. When the values for K are plotted against the moisture tension, a curve like that of fig. 24 is obtained. Note that the value for the loose soil does not fit the curve for the compact soil. At this moisture, much below the saturation, it is expected that there will be a higher hydraulic conductivity in a compact soil.

If an analogous computation is desired for the coefficient of gaseous diffusion, a serious impediment is found. In this case the value for $\frac{dp}{dx}$ is not known, since the vapor pressure to be considered is the one given by the solution of the differential equation 13c which cannot be solved. Since, however, the vapor pressure gradient expected from equation 13c, as shown by fig. 25, has to be smaller than the saturation pressure

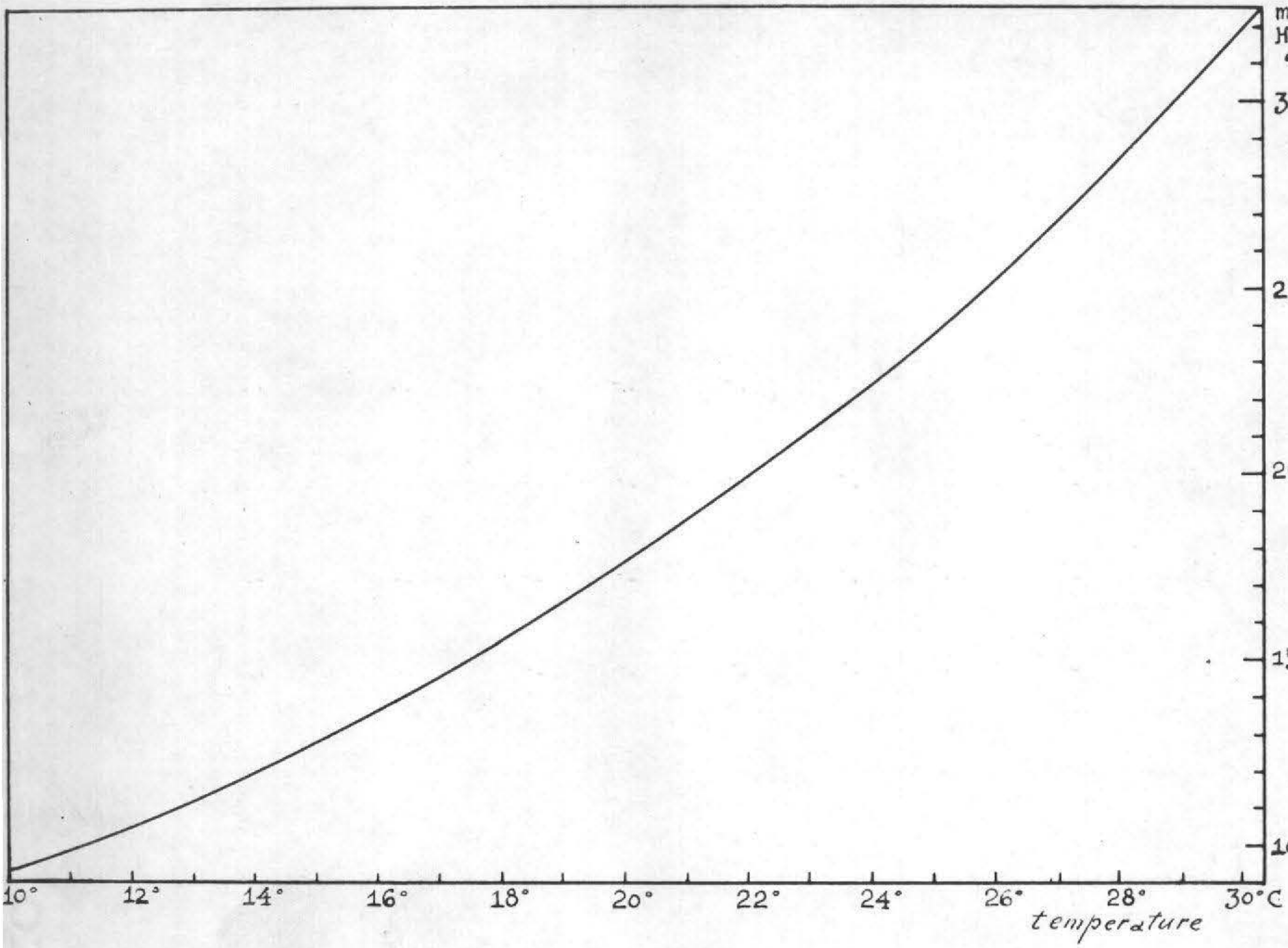

Fig. 23. Saturation vapor pressure as function of the temperature.

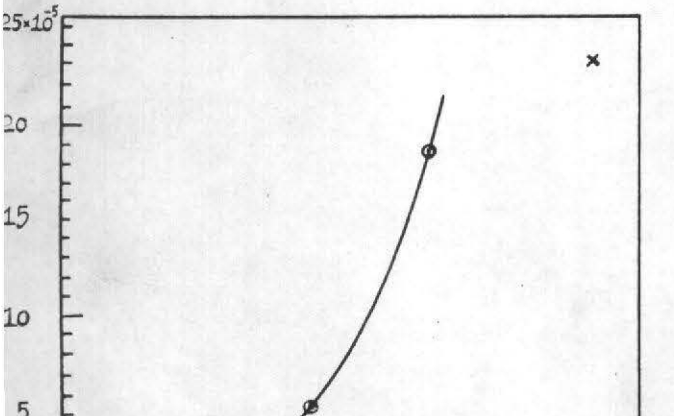

Fig. 24. Hydraulic conductivity as function of the moisture content.

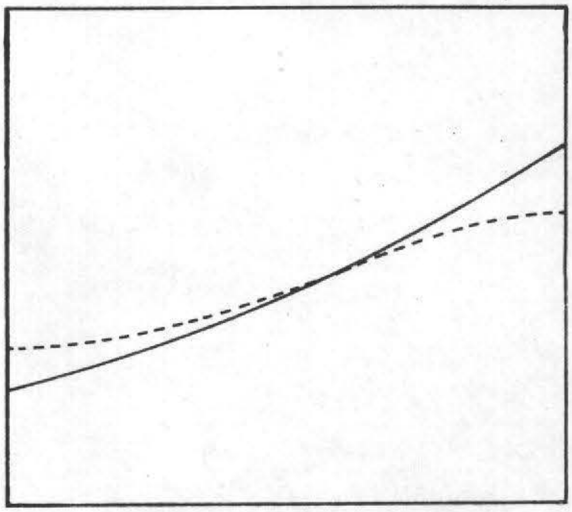

Fig. 25. Supposed vapor pressure curve in a continuous soil cylinder.

gradient, we can compute a minimum value for the coefficient of vapor diffusion by using the latter gradient.

We have:

$$D = \frac{\frac{dq}{dt}}{A\,\frac{dc}{dx}}$$

where D = coefficient of vapor diffusion; c = volume concentration of the water vapor. Considering the middle section of the compact soil cylinder, we observe a vapor concentration gradient of 1.71×10^{-6} g/cm^4 and a vapor flow of 5.79 g /day. The minimum value for D is thus equal to $\overset{1.14}{0.989}$ cm^2/sec. The value for the coefficient of water vapor difussion in air is given by:

$$D_o = 0.2300 \left(\frac{T}{273.1}\right)^{1.75}$$

and at 20° C. is about 0.24. Assuming that the coefficient for the diffusion in the soil column is proportional to the porosity of the soil (Penman (1940), Taylor (1950)), we expect for the column of compact soil a diffusion coefficient about equal to 0.086 cm^2/sec. It is surprising the discrepancy between the expected and the observed value, the latter being at least 11.5 times larger than the former.

Gurr, et al. found also a diffusion coefficient too high, but the difference from the expected value was less since they probably did not consider the vapor condensation occurring far from the cold end.

An explanation for this fact can be found in a paper by Henry (1948). He states that:

> Whenever moisture diffuses through a porous absorbent body the thermal effects accompanying the process result in a coupled diffusion of moisture and heat which is mathematically analagous in many aspects to a pair of coupled vibrations.
>
> The combined diffusion processes can be considered mathematically as equivalent to the independent diffusion of two quantities, each of which is a linear function of both vapor concentration and temperature. These quantities correspond to the normal coordinates of the well known coupled vibration problem. The diffusion constants appropriate to these quantities are always such that one is greater and the other less than either of the diffusion constants which would be observed for the moisture and heat, were these not coupled by the interaction.
>
> This writer observed on cotton bales, that:
>
> > . . . as the temperature rises, the moisture diffusion coefficient D, which is at first much smaller than the thermal diffusion coefficient D, eventually becomes much larger.

Henry points out that these relations are valuable for temperature less than 80° C. and relative humidity less than 90% since under these conditions a liquid flow occurs and takes a remarkable part in the process.

In our case, the fluid flow plays an important role and we cannot entirely apply Henry's conclusions. Also, Henry was dealing with unsteady vapor diffusion. We do not know, therefore, to which extent these facts may be responsible for the high value of the diffusion coefficient observed.

A last point to check is the influence of the distance to the wet front on the moisture content of the drier layers. Since in no case is the minimum value for the moisture below 4%, some values have been calculated for the moisture percentage of a soil layer at various distances from the point at 4%

and 26° C. of temperature. The following formula has been applied:

$$pF = \log_{10} \frac{RT}{gM} \log_{10} \frac{p_o}{p}$$

The pF curve given by Baver for the Greenville loam (the name for which has now been changed to Millville silt loam) was used. Assuming that the same actual vapor pressure, but a different temperature, exists at all points, the following figures were obtained:

distance cm.	Temper. C.	satur. vapor pressure mm Hg	actual vapor pressure mm Hg	Relative humidity	pF	moisture %
0	26	25.209	22.738	90.2	5.42	4.0
0.66	25	23.756	22.738	95.7	4.71	7.2
1.33	24	22.377	22.738	100.0%	-	satur.

It is surprising how rapidly the water tension and the moisture content must change in order to have equilibrium in the vapor phase as the temperature changes. In fig. 1 the change in moisture is very rapid, particularly at about 6.5 cm. from the cold face. The small deviation from the prediction may be easily explained on the basis of the fact that actually at this point there is not equilibrium and liquid flow will probably occur.

These facts, even though some points still require further investigations, permit a better understanding of the principles underlying the moisture transfer in the soil. The particular conditions in which the experiment has been conducted may also apply to the case of water flow from a buried warm surface, e.g., a heated cable, a hot-bed heater. Similarly, it applies for the case of condensation (e.g., against water pipes). If we neglect or modify the considerations concerning the evaporation and condensation at the closed ends of the soil column, a good picture is obtained for the moisture displacement in a free soil mass.

The importance of the diurnal and seasonal temperature variations in the soil are expected to have the effect previously emphasized by many writers.

SUMMARY AND CONCLUSIONS

The movement of moisture in closed soil columns has been theoretically analyzed in its details. Formulas and equations are given and discussed. Predictions have been made.

The experimental results give information concerning the relative importance of the factors involved in moisture transfer, and give confirmation to most of the predictions.

Some other points, such as the influence of changes in the thermal gradient, the interaction between vapor flow and heat flow and its influence on the vapor diffusion coefficient, and the actual moisture retention curve in these conditions remain to be studied.

The following specific statements by way of summary and conclusions may be made.

1. The moisture transfer in the soil under a temperature gradient primarily results from vapor flow. This flow is detectable by the air gap technique. The use of wire screens reduces this flow, but does not impede it completely.

2. The vapor flow is essentially a diffusion process. The convection movement could not be proved.

3. The influence of the variation in the saturation vapor pressure, and its first and second derivatives has not been proved. If it exists it is expected to be negligible.

4. The largest factor affecting the moisture distribution

in a closed soil system, seems to be the evaporation and condensation processes that occur at the warm and cold faces, respectively. The regions involved in this process extend far from the end of the column, and appear to contact at the middle point, smoothly passing from a positive to a negative evaporation.

5. When the soil column is interrupted by an air gap some evaporation and condensation occurs at the faces of the air gap. These processes, however, seem to have very little influence on the overall moisture movement.

6. The thickness of the air gap plays an important role through its influences on the thermal gradient distribution. Its influence on the vapor flow diminishes when the thickness tends to zero.

7. The existence of distinct drying and wetting moisture characteristic curves has been supported.

8. Some values for the moisture conductivity have been computed. Their order of magnitude is reasonable.

9. The coefficient for vapor diffusion has been found much higher than expected. No simple explanation could be found.

10. The dependence of the minimum value for the moisture content at the dry end as a function of the distance to the wet front follows approximately the predictions.

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