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An apparatus to determine vapour pressure in soils above the capillary head*

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(*Received 15 December 1960*)

ABSTRACT. Design and use of simple apparatus to measure vapour pressure in soils and other porous media is described. Readings in both soils and atmosphere are consistent, accurate, reproducible and require no calibration. It is quite easy to operate the apparatus.

1. Introduction

Study of evaporation from top layers of soil is very important both in soil physics and in meteorology. Evaporation is a function of vapour pressure gradient. Determination of vapour pressure within the soil pores might give an insight into what is happening there. This might also tell us where exactly evaporation takes place.

Lebedeff (1927) was one of the first who measured vapour pressure by means of hair hygrometer. Hitoshi Fukuda (1956) used electric hygrometer (Li Cl coated resistance) to find vapour pressure. Chemical instability of hygroscopic substances increases with impurity of absorbed substances with time. Lebedeff and Fukuda came to the conclusion that in natural soil pores, saturation vapour pressure exists unless the soil is very dry. Rocha (1957) measured relative humidity in a cavity in porous materials by means of strains caused on a thin wire by the strains produced in wood by change of relative humidity. But careful calibration is needed in this case. Some measured vapour pressure from a study of the relations between moisture content and relative humidity using static methods, that is, keeping soil in a particular humidity in a closed container. Even many of the dynamic experiments to study this relation are far from actual model. Usually when such experiments are done thin layers of soil are used. These can and will affect actual mechanism of vapour absorption. In nature, soil is in contact with a water table at some depth and with atmosphere at the top. Between these levels water is in continual motion. Hence the soil is in a state of dynamic equilibrium. Study of the methods used by Lebedeff and some others indicate that they used closed containers in which flow of vapour in any direction is almost zero. Thus none of these methods is entirely satisfactory. Hence here a modification of an old technique of measuring vapour pressure in atmosphere is used to measure the vapour pressure in soil pores.

2. Design

Most parts of the apparatus were made of plastic (polyethylene) material since it is easy to fabricate the parts with it. It is transparent and water vapour permeability is very small. Water vapour permeability of polyethylene is 0·04 to 0·08 gm/24 hr/mm/cm Hg at 25°C.

A diffusion tube made of perforated plastic tube (perforation facing downwards) is placed horizontally at a prescribed depth in soil. The ends of the tube emerge from the soil and are connected to a sealed air pump and a sealed dew point hygrometer. The three parts are connected by rubber tubes (0·64 cm diameter) to form a closed path for diffused vapour. The hygrometer is merely a clean

*Part of the Ph. D. Thesis submitted at the Department of Meteorology, University of Washington, Seattle, Washington, U. S. A.

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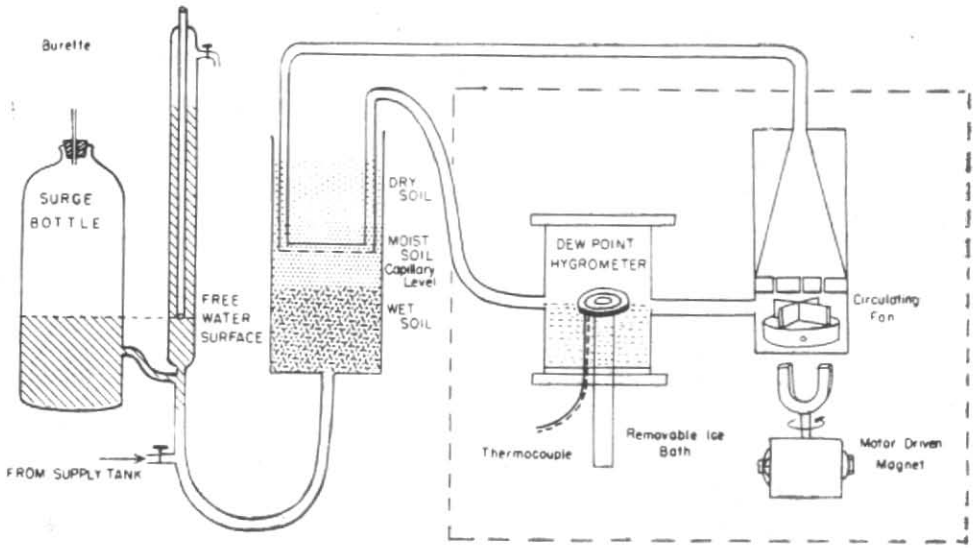

FIG. 1. APPARATUS TO DETERMINE VAPOR PRESSURE AND EVAPORATION

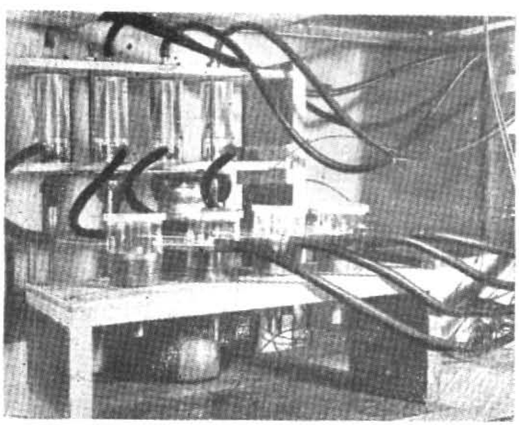

FIG. 1. (a) A VIEW OF THE FAN CONTAINERS TOGETHER WITH HYGROMETERS AND HORSE SHOE MAGNETS JUST BELOW THE FAN CONTAINERS

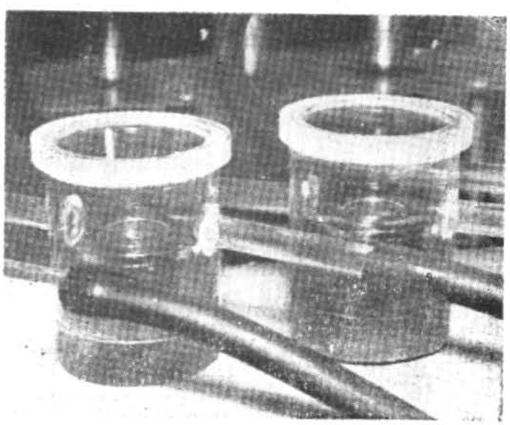

FIG. 1. (b) HYGROMETERS

polished metal surface which may be cooled until dew starts to form. The temperature of dew point is measured by means of thermocouple and that can be translated into vapour pressure. The sketch of the apparatus is given in Fig. 1. The photographs of the apparatus are given in Figs. 1a and 1b. The details of the relevant parts of the apparatus are given below—

Diffusion tube—This is made of plastic tube of internal diamter 0·64 cm. It has a U shape. The straight bottom part of the tube, 12 cm long, is perforated with a number of holes of diameter 0·3 cm so that the total area of the holes is not more than 2 sq. cm.

Fan—The fan is made of 4 copper blades. Each blade is 1 cm square. It is fixed symmetrically on the plane side of a teflon (a plastic material) disk of 0·6 cm thickness and 4·5 cm diameter. Through a diameter of the disk a hole of 0·4 cm diameter is drilled and a cylindrical magnet of 0·4 cm diameter and 4·3 cm length is introduced symmetrically into the hole. Teflon is not wetted by water and is insoluble in water. Adsorption of water by teflon is very small even at high relative humidity. No heat is developed by friction between teflon and other surfaces (metal and polyethylene) even when the teflon disk fitted with the fan is rotating at 1800 revolutions per minute.

Fan container—It consists of an upper part which is a hollow cone and a lower part a hollow cylinder. The hollow cylinder is made of a plastic tube of internal diameter 4·6 cm, external diameter 5 cm and height 3 cm. There is a side tube of 0·64 cm diameter at a height of 1 cm above the closed bottom of the cylinder.

The hollow cone is made from a transparent solid plastic cylinder of 5 cm diameter and 10 cm height. At the apex of the cone there is a hole of 0·64 cm diameter which is connected to a short plastic tube of equal diameter. The lower end of the cone is closed by a perforated plastic disk of diameter 4·6 cm; the perforation making a total area half that of a hole of 0·64 cm diameter. The bottom of the hollow cone which is the perforated disk, caps the open end of the cylinder. A little vaseline at the rim makes the capping air tight. The conical shape makes the downward flow of air through the cone very smooth. The teflon disk fitted with the fan is rotated by means of a horse shoe magnet kept just below the cylinder containing the fan. The horse shoe magnet is rotated by means of a motor of 1800 revolutions per minute.

Hygrometer—A hole of 0·2 cm diameter and depth of 0·64 cm is drilled 0·05 cm below one plane end of a copper cylinder of 1·28 cm diameter and 12 cm length. A junction of copper constantan thermocouple of adequate length is introduced and fixed into the drilled hole. A plastic cylinder 6 cm diameter is cast concentrically around half the length of the copper cylinder, the half which has the thermocouple. The other half of the copper cylinder protrudes downwards from the plastic cylinder together with the thermocouple wires. A circular groove of 5 cm external diameter, 3 cm internal diameter and 0·3 cm even depth is cut into the plastic on the plane end of the plastic-cum-copper cylinder. This groove is filled with a copper disk of dimensions identical with the groove. The plane end is polished and the copper surfaces are nickel plated to equal brightness. This end is capped air tight with a transparent hollow plastic cylinder of internal diameter 6 cm such that the top of the cap is 1 cm above the nickel plated surfaces. Two side tubes of 0·64 cm diameter each open into the cap just above the place of the nickel plated surfaces. The tubes are fixed at diametrically opposite sides of the cap. One tube connects the fan container and the other the diffusion tube. This hygrometer is simply a modified and improved form of Regnault's dew point hygrometer. Hence all the merits of Regnault's apparatus exist, while the demerits have been reduced in the modified form. In this modified form the temperature of the surface where dew is formed is measured accurately and there is ventilation of air at the surface where dew is formed. Since the characteristics of the dew point hygrometer are known, no attempt was made to determine it in the case of the modified form.

3. Method of measurement

To find the vapour pressure in soil pores, at the level of diffusion tube, the following procedure is used. First the pump is allowed to work for about 3 hours. Then while the pump is working the bare copper rod of the hygrometer projecting downward is cooled. This cools the nickel plated surface of the rod. When surface temperature reaches the dew point, dew starts to appear on the nickel plated end. This can be easily detected by comparing the brightness of the two nickel plated surfaces. The temperature of the surface is noted by means of the thermocouple both when dew appears and when it disappears. The average temperature is then taken as the dew point and the dew point translated into vapour pressure. Different sets of apparatus are used to measure simultaneously vapour pressure at different depths in the soil. All the fans work at the same speed. This method is used both in field and laboratory. In Fig. 1 the large plastic tube (height 92·5 cm and diameter 20·32 cm) containing soil is supplied by water from the bottom of the large plastic tube at a constant pressure head from a burette. When water movement in the soil has reached a steady state the rate of water supply from the burette will be equal to evaporation. The evaporation in field can be found by diffusion method or energy balance method or evaporimeter method (Sutton 1953).

4. Experimental results

Vapour pressure in soils at different depths is measured by the apparatus in both field and laboratory. The atmospheric vapour pressure measured by the apparatus is always in complete agreement with that determined by means of other common hygrometers. Vapour pressure at the capillary head is always saturation vapour pressure*. When soil moisture and temperature are constant at each level, vapour pressure readings are also constant and reproducible at the same level. The vapour pressure above the capillary head even in moist soil is less than saturation vapour pressure and vapour pressure gradient is nonlinear. In field also when moisture content is less than field capacity, vapour pressure is less than saturation vapour pressure. Some typical graphs showing the relation between vapour pressure (or relative humidity) and depth below surface (or height above the capillary head) are shown in Figs. 2-4. The graphs 3 and 4 need some explanation. Those graphs show the results of laboratory experiments while graph 2 shows that of field experiments. Considering graphs 3 and 4 it is to be noted that though the vapour pressure gradient is very strong in the moist soil just above the capillary head, the vapour transfer will be very small since the porosity of that region is very small. John (1957, 1958) has shown that there is surface diffusion in addition to vapour diffusion in all layers of soil above the capillary head. In the top layers the main mechanism of water transfer is by vapour diffusion.

5. Discussions

It was realized that a pressure difference created between the pumping system and outside air could, if great enough, cause a mixing of soil air with outside air. Consequently this pressure difference was estimated by means of Poiseuille's equation (*Handbook of Meteorology*, p. 448).

$$V = \pi\, a^4(P_1 - P_2)/8\mu L$$

where V is the discharge of air through the cross-section of the tube connecting the pumping system per second, a is the radius of the tube conncting the pumping system, μ is the viscosity of air, L is the length of the pumping system and $(P_1 - P_2)$ or $\triangle P$ is the pressure difference created in the pumping system. V was determined by

*Capillary head is the point above the free water surface (water table) up to which water will rise due to surface tension and is determined by the usual experiment to find the rise of water in capillary tubes

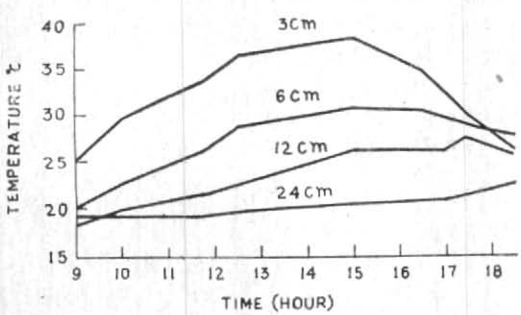

FIG. 2 (a). TEMPERATURE VERSUS TIME AT 3, 6, 12 AND 24 cm BELOW THE SURFACE

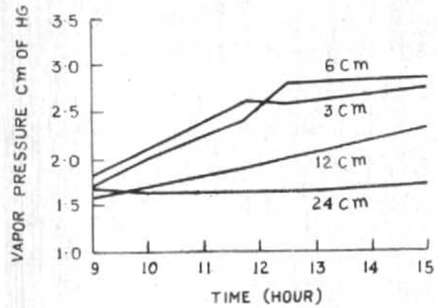

FIG. 2 (b). VAPOR PRESSURE VERSUS TIME AT 3, 6, 12 AND 24 cm BELOW THE SURFACE

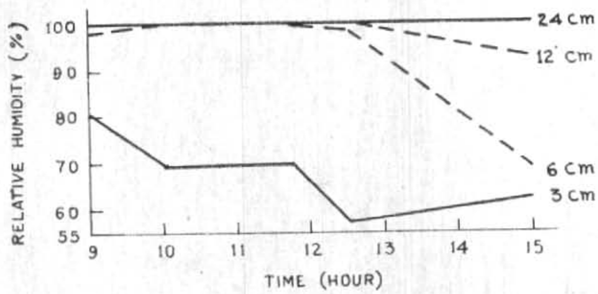

FIG. 2. (C). RELATIVE HUMIDITY VERSUS TIME AT 3, 6, 12 AND 24 cm BELOW THE SURFACE

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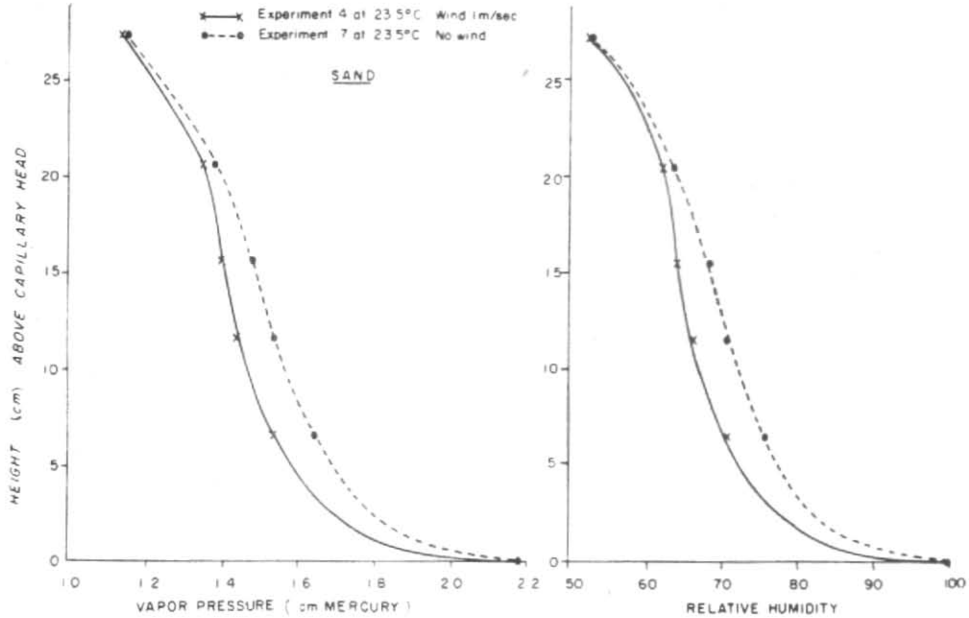
movement of smoke in the tube. In a typical experiment this was $\pm$ $(1{\cdot}25)10^{-5}$ cm of mercury. The permeability of sand is more than that of any other soil and the top layer of soil above the capillary head will have more permeability since it contains less moisture than lower layers. Hence an estimate of mixing of outside air with soil air in the diffusion tube produced by pumping in the top layers of sand (average diameter 0·077 cm) was made from the known pressure difference created by the pumping system by means of Kirkham's formula

$$dq/dt = (k/\mu)\, A\, (\triangle P/760) / L$$

where k is permeability* of the soil in darcys, μ is viscosity of air in centipoises, $\triangle P$ is the pressure difference in mm of mercury, L is the thickness of soil layer in cm, A is area of cross-section of the soil column through which air is assumed to flow and dq/dt is the rate of escape in cc/sec.

For the sand the permeability is 600 darcys (ref. *Physics Handbook*), the viscosity of air 0·018 centipoise at room temperature, L was 5 cm, $\triangle P$ was $(1{\cdot}25)10^{-5}$ cm of mercury, and A was 1 sq. cm. Having applied these values in the above equation dq/dt was found to be $(1{\cdot}05)10^{-3}$ cc per sec or 3·78 cc/hr. The total volume of the pumping system was about 190 cc, hence the percentage of mixing was less than 2 per cent per hour. This amount of mixing would result in a change in relative humidity of only 0·1 per cent which is within the experimental error. Therefore, it was concluded that the error introduced by the pumping was insignificant.

*A porous structure will have a permeability of one darcy if, for a fluid of one centipoise viscosity, the volume flow is 1 cc per sq. cm area under pressure gradient of 1 atmosphere per cm



VAPOR PRESSURE VERSUS HEIGHT ABOVE CAPILLARY HEAD

RELATIVE HUMIDITY VERSUS HEIGHT ABOVE CAPILLARY HEAD

FIG. 3

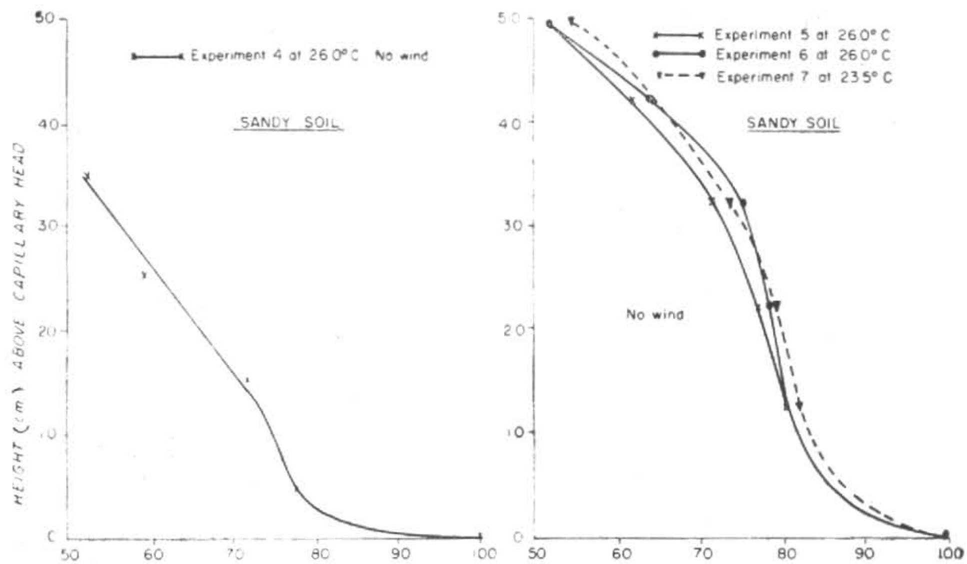


FIG 4 RELATIVE HUMIDITY VERSUS HEIGHT ABOVE CAPILLARY HEAD
(Based on data obtained from laboratory experiments)

In field it is found that serious error can result from a difference between the temperature of soil and outside air. Hence to avoid this effect the whole pumping system except those parts that lie in the plane of the perforated tube is well insulated. About 75 per cent of the tube in the pumping system is kept in the plane containing the perforated tube in order to keep the air in the pumping system nearer to the soil temperature in that layer. This can be improved further by keeping the pumping system at the temperature of soil by some thermostatic mechanism. This method can also be used to measure vapour pressure in other porous media.*

6. Conclusions

An apparatus to measure vapour pressure in soil pores was designed, constructed and used. This method can be used both inside the laboratory and in the field outside. The method is simple, consistent, accurate, reproducible and needs no calibration.

7. Acknowledgement

The author feels it a pleasure to express his gratitude to Prof. F.I. Badgely for his keen interest and encouragement during the progress of this work.

The author expresses his appreciation for the support of this research by the U. S. Atomic Energy Commission through the Eddy Diffusivity Contract at the University of Washington.

*See author's thesis for detail

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