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Investigations on the relation between relative humidity of soil air and soil temperature

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ABSTRACT. It is shown mathematically and experimentally that relative humidity of soil air is almost independent of temperature.

1. Introduction

Relative humidity of soil air is a function of moisture content of soil but its relation to temperature is not fully understood. Condensation into soil and evaporation from soil depends on relative humidity of soil air. Information on relative humidity of soil air is very useful for civil engineers, agriculturists and meteorologists.

Lebedeff (1927) was one of the first to determine relative humidity of soil air. He found it by means of hair hygrometer. He concluded that (*a*) when soil moisture is less than its hygroscopy, then R.H. is less than 100 per cent, (*b*) drier the soil less the R.H. and (*c*) when soil moisture content is constant, with temperature, R.H. of soil air increases. Puri (1939) determined the relation between soil moisture and relative humidity of soil air by keeping soil in a particular humidity in a closed container or by passing of air of particular humidity through the soil for a long time. He concluded that R.H. is independent of soil temperature at high humidity and that it varies with temperature at low humidity. de Boer (1953) stated that adsorption equilibrium (between an adsorbent and an adsorbate) will establish itself practically instantaneously. If this is not the case in practical examples, we must seek cause in transport problem. Fukuda (1956) used electric hygrometer to determine R.H. in soil pores. He concluded that R.H. below 100 per cent depends principally on soil moisture and little, if any, on soil temperature. de Vries and Philip (1957) found an optimum value for relative humidity of soil, below which only, the variation of relative humidity was independent of temperature. Rocha (1957) determined R.H. in a cavity by means of strain produced in wood prisms with the absorption of moisture from air. He stated that R. H. will decrease with decrease of temperature if the medium is an adsorbing medium. Accurate calibrations are needed in all the above methods used to determine relative humidity. Decrease of relative humidity of soil air can also occur due to the presence of various salts in soil water.

2. Theory

John (1962) has shown that the differential equation of diffusion of vapour in an isothermal soil column is

$$D(d^2p/dn^2) - cvp = 0 \tag{1}$$

and that its solution is

$$p_n = p_s \exp(-Kn/2) \tag{2}$$

The above solution can be written as

$$p_n = p_0 \exp(Km/2) \tag{3}$$

In the above equations $D = D_0 vb$ and $K = 2\sqrt{(c/D_0 b)}$. The symbols D and D_0 represent diffusion constants in soil and air respectively, c is a constant, b is another constant whose value according to de Vries (1950) is 0·66, v is porosity of soil, p represents vapour pressure, p_s , p_0 , p_n respectively are vapour pressures at the lower boundary, at the upper boundary and that at h distance below the upper boundary. p_n can also be defined as the vapour pressure at h_1 distance above the lower boundary. Hence $h_1 + h = H$. From boundary conditions it can be shown that

$$K = -\ln(p_0/p_s) \tag{4}$$

$$n = (h_1/H) + (w_c - w_z)/(w_c - w_0)$$
$$= (h_1/H) + (w_1/W) \tag{5}$$

$$m=(h/H)+(w_z-w_0)/(w_c-w_0)$$
$$=(h/H)+(w/W) \qquad (6)$$

Here w_c, w_0, w_z respectively are the moisture contents at the lower boundary, at the upper boundary and at h distance below the upper boundary. Now Clausius–Clapeyron equation for saturated vapour, within a small range of temperature can be expressed as (consider p_s as saturation vapour pressure)

$$p_s = \exp(A-B/T) \qquad (7)$$

where A and B are constants and T is temperature in degrees absolute. If r_0 is the relative humidity at the surface of the soil column, then since $p_0=p_s\, r_0$

$$p_0 = r_0 \exp(A-B/T) \qquad (8)$$

Substituting eq. (8) in eq. (3), one gets

$$p_h = r_0 \exp(A-B/T) \exp(Km/2) \qquad (9)$$

It is clear from equation (4) that

$$p_0=p_s \exp(-K)$$

$$\text{or} \quad r_0 = \exp(-K) \qquad (10)$$

Substituting equation (10) in equation (9) one gets after re-arranging

$$p_h = \exp(A^*-B/T) \qquad (11)$$

$$\text{where} \quad A^*=A+K\,(w/W+h/H-2)/2 \qquad (12)$$

The equation (11) gives the vapour pressure p_h at a depth h from the surface of the soil column. At the capillary head, H distance below the surface of the soil column, w/W and h/H become 1 each and hence equation (12) reduces to equation (7). Dividing equation (11) by equation (7), one could determine the relative humidity r_h, *i.e.*,

$$r_h = \exp(A^*-B/T)/\exp(A-B/T)$$
$$=\exp(A^*-A) \qquad (13)$$

Equations (11) and (7) are valid only for a small range of temperature of the order of 10°C. It is clear from equation (13) that relative humidity r_h is independent of temperature provided A^* remains a constant in this range. Note that moisture content w_c, w_0, and w_z need not be constant to keep w/W as a constant. This point is discussed further (Sec. 4).

3. Method and Observations

Vapour pressure of the soil pores was measured by the author (1961 a) by means of a modified form of Regnault's dew point hygrometer. Temperature at each level of vapour pressure observation, was measured by means of thermocouple. Since the author (1961 b) has already given a full description of experiments, these will not be repeated here.

Field experiments were done during the summer months of July-August, in a clayey area where some short grass was growing. During the period (14 July to 18 August 1956) of observations, only on two days (2 and 15 August) there was light rain and on many days there was light fog in the early mornings. The experimental area was in Friday Harbor in the state of Washington, U.S.A. This area was near a very large lake, whose water temperature is almost always, round about 10°C. The cool land breeze caused fog near about the coast line and hence high humidity of air during the early hours of mornings. Vapour pressure and temperature were measured at depths 3, 6, 12 and 24 cm. Day after day the observations for each level were almost similar. Hence only some typical data are given in Table 1.

First on a semi-log paper, vapour pressure–temperature relation for water was plotted by choosing temperature scale in such a way as to give a straight line. (Pressure was plotted on log axis and temperature on the x-axis). Then on the same paper, the observed vapour pressure—temperature relations of soil moisture for each level for the period 0900 to 1600 were plotted and best fit straight lines were drawn for each level. Now choosing two temperatures and the corresponding vapour pressures from each of the straight lines shown in Fig. 1, equation similar to equation (7) was formed for the levels —3, —6 and —24 cm. They are

$$\log p_{-3} = 8\cdot891-2290/T \qquad (14)$$

$$\log p_{-6} = 8\cdot981-2290/T \qquad (15)$$

$$\log p_{-24} = 9\cdot053-2290/T \qquad (16)$$

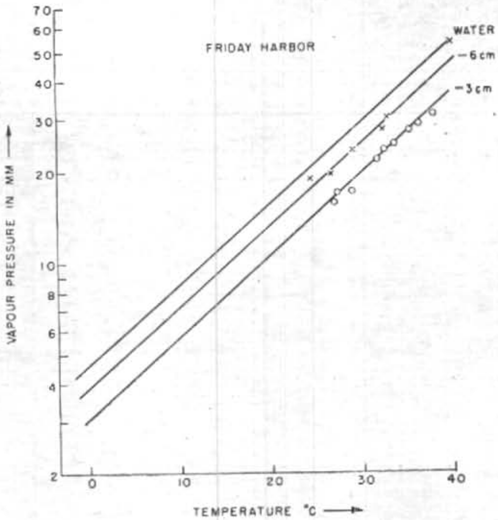

Fig. 1. Vapour pressure *vs* temperature (Linear graph)

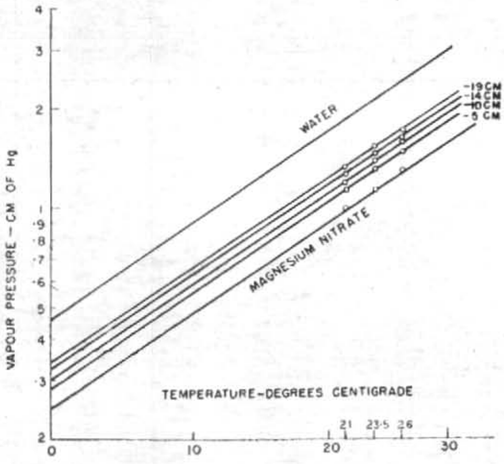

Fig. 2. Vapour pressure *vs* temperature (Linear graph)

These equations, in general, gave the values of vapour pressure for the period 0900 to 1600 hrs. But for other periods, these equations are not valid because of many reasons which are given later in this paper. A simple calculation using equation (14) showed that the temperature coefficient of R.H. is almost negligible. The spread of points plotted for the level –12 cm was very much showing variable moisture content for the level even during the period 0900 to 1600 hrs. This brings out that the law of conservation of R.H. within a certain range of temperature will not hold good for the level where moisture transport (both upward and downward) is high. Equation (16) is identical with equation for vapour pressure—temperature relation of saturated vapour for the range of temperature that existed in the field. Relative humidity for the level –3 cm is given in Table 1. The mean relative humidity for the levels –3 cm and –6 cm are 68 per cent and 85 per cent respectively.

From the meagre data that could be collected the R. H. does not appear to be dependent on temperature.

Laboratory experiments were done using sand and sandy soil kept in large plastic tubes of length 91·5 cm and area of cross-section 323·5 sq. cm. Vapour pressure was measured at four levels in each of the soil, in between capillary head and surface of the soil column. The experiments were repeated at different temperatures. The room humidity was kept at about 52 per cent by exposing 36 square feet of saturated solution of magnesium nitrate. John (1961 b) has given a full description of the experiments. Some typical experimental results are given in Table 2. Graphs similar to Fig. 1 were drawn for sand and they are shown in Fig. 2. One might object to the straight lines drawn by joining only three experimental points. But since all the lines drawn for different levels are parallel to the line drawn for water, there is sufficient reason to justify the validity of Fig. 2. The equation showing the relation between the vapour pressure and temperature of soil moisture at level —19 cm in sand is

$$\log p_{-19} = 8 \cdot 921 - 2290/T \qquad (17)$$

The observed and the calculated values using the above equations are given in Table 3.

It is clear from Table 2, that the R.H. in sandy soil is almost independent of temperature. The author attributes the small changes seen in the relative humidity in

TABLE 1

Vapour pressure and relative humidity with depth in clayey soil (Friday Harbor, Washington, August 1956)

Date	Time	Observed temp. (°C) —3 cm	Observed vap. pr. (mm of Hg) —3 cm	Relative humidity (%)	Remarks
10	1130	22·30	14·47	83·9	Cloudy up to 1200 hrs
	1330	28·94	20·60	69·5	
	1530	30·15	22·20	69·9	Stopped due to other work
11	1000	25·27	15·17	63·5	
	1100	27·96	16·66	65·5	
	1200	32·09	23·87	67·3	Stopped due to other work
12	0900	25·52	19·40	80·1	Very foggy morning
	1000	30·15	22·19	69·9	
	1145	34·02	27·68	69·9	
	1500	37·38	29·72	62·3	
	1630	35·22	28·01	66·2	
	1730	30·15	23·90	75·1	
	1830	26·98	26·31	100·0	

TABLE 2

Relation between relative humidity and height above the water table

Sandy soil			Sand			
Height above water table (cm)	Relative humidity at		Height above water table (cm)	Relative humidity at		
	23·5°C	26°C		21°C	23·5°C	26°C
20†	100·0	100·0	4·0†	100·0	100·0	100·0
32	80·9	80·0	10·5	71·0	75·8	75·5
42	74·0	76·5	15·5	67·7	71·1	73·3
52	71·1	72·0	19·5	62·7	66·8	70·9
62	62·6	61·8	24·5	58·5	63·1	67·9
72	52·5*	52·0*	31·5	53·0*	52·5*	52·0*

†Capillary head. *Room humidity. Height of sandy soil column was 69·5 cm at 26°C and that of sand column was 29·5 cm at 21°C

TABLE 3

Vapour pressure calculated using equation (17)

(at —19 cm in sand)

Temperature (°C)	Vapour pressure (mm)	
	measured	calculated
21·0	13·16	13·71
23·5	16·41	15·96
26·0	18·54	18·58

sandy soil, to the slight change in the height of the soil column and that of room humidity (see foot note below Table 2). It is also clear from Table 3 that equation similar to equation (17) can be used to predict vapour pressure in any soil air with the change of temperature within a small range. This fact could be guessed from Figs. 1 and 2.

4. Discussions

de Boer (1953) showed that the difficulty to reach adsorption equilibrium in a porous medium is due to transport problem. But in steady state cases there will be adsorption equilibrium. For example, when the temperature of an isothermal soil column at steady state is changed to a new isothermal value the balance between volume diffusion and surface diffusion is readjusted in addition to the balance between vapour pressure and moisture adsorbed. In such cases, as seen for sandy soil in Table 2, relative humidity at each level remains almost unchanged. Fukuda's (1956) observations agree with this view. In sand there is an increase of humidity with temperature. The reasons for this are not very clear. But it appears that this may be due to uneven decrease of adsorptive force with temperature. The author after studying the relation between relative humidity and moisture content of soil, timber, cotton, leather etc is of the opinion, that at steady state, relative humidity is almost independent of a small range of temperature. At this range of temperature, relative moisture content $(w_z - w_0)/(w_c - w_0)$ is almost a constant. It is clear from equation (13) that R. H. will remain as a constant provided relative moisture content w/W is a constant. Taking one upper humidity value r_s and a lower humidity value r_0 as standards, one could redefine relative moisture content at r_n as given below—

$$\text{Relative moisture content at } r_n = \frac{(\text{Moisture content at } r_n) - (\text{moisture content at } r_0)}{(\text{Moisture content at } r_s) - (\text{moisture content at } r_0)}$$

Here $r_0 < r_n < r_s$ and they are all in the same phase of adsorption. They should not be values from two-phase adsorption.

In field experiments adsorption equilibrium is not reached fast enough to keep the relative humidity constant. As stated earlier, this difficulty is due to transport problem. In other words, but for transport problem, relative humidity of soil air in field also would remain almost unchanged within a range of temperature, say 10°C. Smith (1943) found that the thermal transfer of moisture is negligible at very low and at very high moisture contents. This implies that at unsteady state, change in relative humidity will be less at low and high moisture contents. This is the case specially at –3 cm in the experimental area during the period 0900 to 1600 hrs on every day. But on late evenings and at night, moisture transfer from the atmosphere takes place into the top layers of soil. Hence R.H. increases during the period. At –12 cm, moisture content is not low and hence the thermal transfer of moisture will be much. This accounts for the large variation of relative humidity during the period 0900 to 1600 hrs.

5. Conclusions

(*a*) At low moisture content (low R.H.), with temperature moisture transfer is low, but diffusion increases. Hence R.H. will slightly decrease.

(*b*) At high moisture content (high R.H.), with temperature moisture transfer is high, but diffusion decreases. Hence R.H. will increase slightly.

(*c*) At steady state isothermal cases, it appears from soil data, that R. H. is almost independent of temperature.

6. Acknowledgement

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Appendix I

Symbols

A a constant

A^* $A+K(w/W+h/H-2)/2$

B a constant

b a constant in the diffusion equation and it is equal to 0·66

c a constant

D diffusion constant of water vapour in soil

D_0 diffusion constant of water vapour in air

h depth below the surface of the soil column where the vapour pressure is p_n

h_1 height above the capillary head, where the vapour pressure is p_n

H length of the soil column, *i.e.*, $h_1+h=H$

K $-\ln(p_0/p_s)$, also equal to $2\sqrt{c/D_0 b}$

m $h/H+w/W$

n $h_1/H+w_1/W$

p vapour pressure

p_0 vapour pressure at the surface of the soil column

p_n vapour pressure at depth h below the surface of the soil column

p_s vapour pressure at the lower boundary or saturation vapour pressure

r_0 R.H. at the surface of the soil column or a lower standard humidity value

r_n R.H. at h distance below the surface or a R.H. value between r_0 and r_s

r_s R. H. at the lower boundary or an upper standard humidity value

T temperature in °A

v porosity

w_0 moisture content at the surface of the soil column

w_z moisture content at h distance below the surface of the soil column

w_c moisture content at the capillary head

w_1 w_c-w_z

w w_z-w_0

W w_c-w_0