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THE MECHANISM BY WHICH WATER MOVES THROUGH A POROUS MATERIAL SUBJECTED TO A TEMPERATURE GRADIENT: I. INTRODUCTION OF A VAPOR GAP INTO A SATURATED SYSTEM

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Although the movement, due to a temperature gradient, of moisture through porous materials has been studied by many workers, the mechanism by which moisture moves through such materials remains a point of controversy (1, 5, 11, 13, 14). There are two theories which lead to two generally accepted and possible mechanisms. The first theory postulates that the moisture moves from hot to cold regions in the vapor phase and that the driving potential is the vapor pressure difference which corresponds to the temperature difference. Strong evidence in favor of this mechanism is the absence of moisture movement due to a temperature gradient in a fully saturated system where there is no vapor phase (6). The second theory postulates that some of the water moves in the liquid phase in the form of a film. This concept was put forward to account for the fact that the experimentally observed rate of movement is about ten times as large as the calculated rate based on vapor diffusion (1, 14).

Some experiments to study the mechanism of moisture movement due to a temperature gradient through porous materials have been carried out in this laboratory. This paper deals with the influence of a gap (of vapor) on the rate of movement in an otherwise saturated system.

APPARATUS AND PROCEDURE

The theoretical relationships involved and the practical aspects of the construction of the apparatus have been described by others (4, 9). The main principle involved is that, under isothermal conditions, the moisture content of a porous material in contact with a saturated porous plate is determined by the difference in pressure across the plate. The moisture content decreases as the difference in pressure increases. This difference in pressure is also frequently referred to as the suction (4, 10). The maximum pressure difference that can be used is less than the pressure required to empty the pores of the plate. This pressure is given by the equation:

$$P = \frac{\gamma}{m} \qquad (1)$$

where

P is the pressure (dynes/cm.^{2})

γ is the surface tension (dynes/cm.)

m is the hydraulic radius (ratio of area of pore to perimeter of pore) (cm.) (2)

[1] This paper is a contribution from the Division of Building Research, National Research Council, Canada, and is published with the approval of the Director.

In equation (*1*) the contact angle between the water and the porous plate is assumed to be zero. The contact angle between water and the clean surfaces of a material such as that constituting the porous plate used in the present experiment has been shown to be zero or very small (8). Also, the relative humidity, in excess of 99.9 per cent, maintained within the apparatus favors a contact angle of zero.

The apparatus used in the present investigation was a modification of that developed by Swenson and Sereda (12) to maintain a fixed moisture content in a sample at the same time that the movement of moisture due to a temperature gradient is taking place. Since work in which the apparatus was used to regulate the moisture content of a sample will be reported in a subsequent paper (7), the functioning of the apparatus with as well as without a sample will be described at this time.

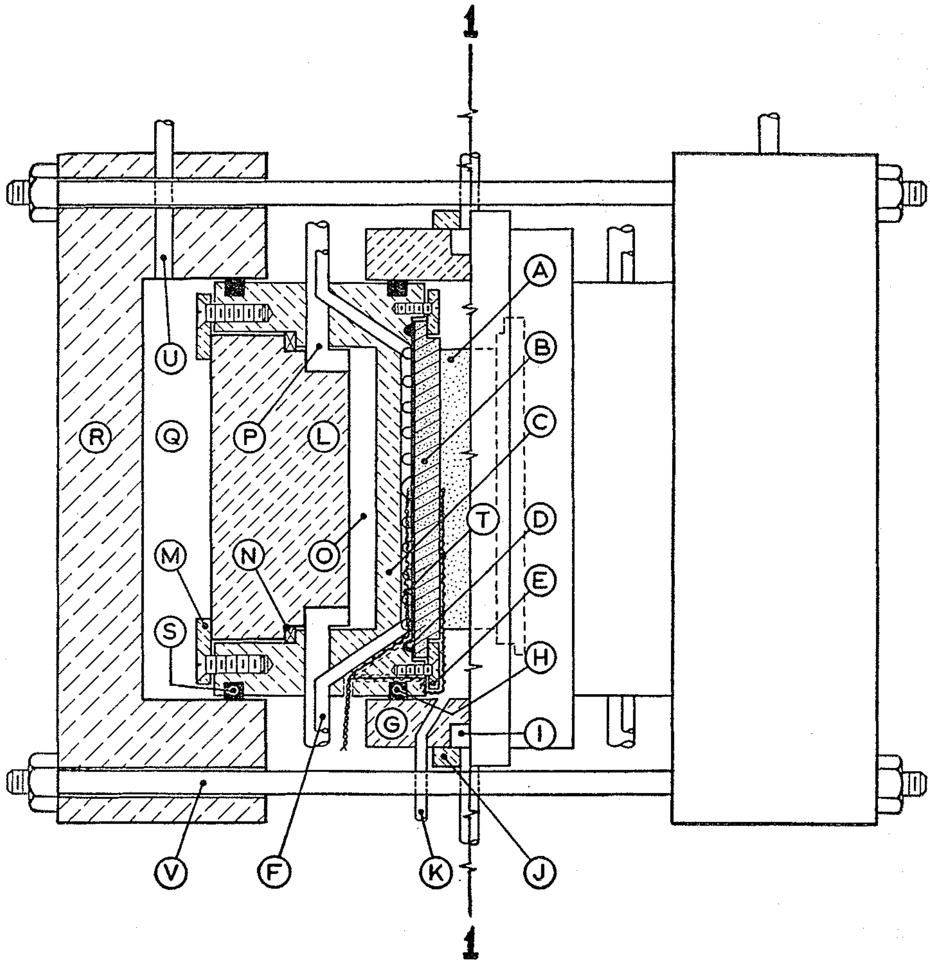

FIG. 1. MOISTURE TRANSFER APPARATUS

The apparatus is shown in half section in figure 1. A cylindrical sample A was confined by two identical ceramic porous plates B which were sealed into cylindrical lucite sections C by rubber "O" rings D and fibre rings E. The other side of the porous plates was kept in contact with water at atmospheric pressure. The grooved reservoir holding this water was connected to horizontal measuring pipettes by glass tubing F. The space surrounding the sample was confined by a lucite ring G and rubber seals H. This arrangement permitted the two porous plates to come into alignment with the two faces of the sample and to remain so throughout the experiment. To prevent condensation on the ring G, heated water from a constant temperature bath was circulated through the circumferential groove I. This groove was confined by a tightly fitting lucite ring J.

Air at any given pressure, controlled by a pressure regulator, was introduced into the space around the sample through a tube K. The pressure was read from a mercury manometer. Pressures larger than those which could be read on the manometer were read on the gauge of the pressure regulator. Since the pressure on the other side of the porous plate was atmospheric, the manometer pressure gave the pressure difference or suction to which the sample was subjected. By varying this pressure, the moisture content of the sample was varied.

The cylindrical spaces O were confined by the lucite plugs L which were retained by brass rings M and sealed by rubber rings N. To produce a temperature difference across the sample, the spaces O were connected by tubing P to sources of water controlled at two different constant temperatures. During the movement of moisture due to this temperature difference, the porous plate at the higher temperature acted as a source of water while the other acted as a sink.

The outer lucite cylinders R permitted parts C and their assembly to function as pistons. The seals S allowed the parts to slide freely. Firm contact of the porous plates against the faces of the sample was achieved by an air pressure in the spaces Q larger than that in the space surrounding the sample. The difference in pressure between these two spaces was kept constant at 135 cm. of water in order to maintain a constant contact pressure between sample and porous plates. The air was admitted into the space Q through metal tubing U.

To measure temperatures inside the apparatus, copper-constantan thermocouples T were brought out through small holes in the body of part C. The holes were sealed up with wax. The entire assembly was held together by six tie bolts V.

In the present experiment, the apparatus was used without a sample between the porous plates. The faces of the two porous plates were brought in contact with one another. Because the faces were planar, there were numerous points of contact. This produced a definite pore system at the interface. It was the effect of the gap composed of these pores as well as the effect of the gap between the separated plates that was studied.

The gap was varied as follows. The pore system at the interface was varied by altering the texture of the surface of the faces by grinding them with carborundum powder, No. 80 to produce a coarse surface and No. 600 to produce a fine surface. A rotating automatic polishing machine was used to ensure that

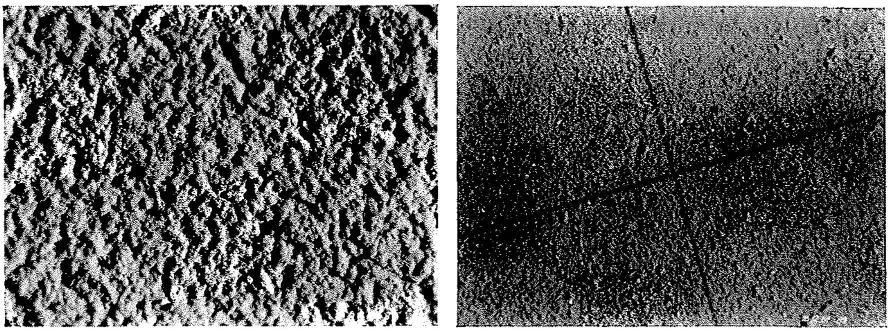

FIG. 2. ×21. SURFACE OF POROUS PLATE GROUND WITH CARBORUNDUM POWDER No. 80 (*left*) AND No. 600 (*right*)

the faces were planar. The texture of these surfaces is shown in figure 2, left and right, respectively. Next, the fine surfaces were separated by four shims, equally spaced around the perimeter, between the two porous plates. Shims 0.0025 and 0.119 cm. thick were used; each shim was 0.4 cm. square.

A temperature gradient across the two porous plates was imposed, as described, by circulating water at 0.6°C. through one side of the apparatus and water at 49.0°C. through the other. When the 0.119 cm. shims were used, an attempt was made to get a rough idea of the temperature of the surfaces across the gap by placing No. 30 B and S gauge copper-constantan thermocouples on these surfaces. It was realized that the temperatures obtained in this manner would likely be in error since the size of the actual junction of the thermocouple wires is relatively large when compared with the distance between the plates. For the thinner shims and for the experiments with no shims, no attempt was made to obtain this temperature. However, to ascertain whether the temperature across the plates varied during an experiment, thermocouples were placed in contact with the outside surfaces of the plates.

The quantity of water in the gap was varied by varying the air pressure in the chamber supplied through tube K. Contact between the plates was maintained by an opposing pressure as described.

The rate of flow of the water was obtained by observing the rate of movement of the menisci in the two horizontal pipettes. Two pipettes were used, one to indicate the flow into the system, the other to indicate the flow out. A steady-state condition was indicated when these rates were equal.

The rate of flow through the porous plates due to a hydraulic head was measured.

The porous plates were 7.6 cm. in diameter and about 0.76 cm. in thickness. The pressure required to empty the pores was experimentally determined as 5000 cm. of water.

RESULTS

For the four gaps used, figure 3 shows the relationship between the rate of flow due to the temperature gradient and the pressure used to unsaturate the gap. Each curve is the average of three runs which were in good agreement. A

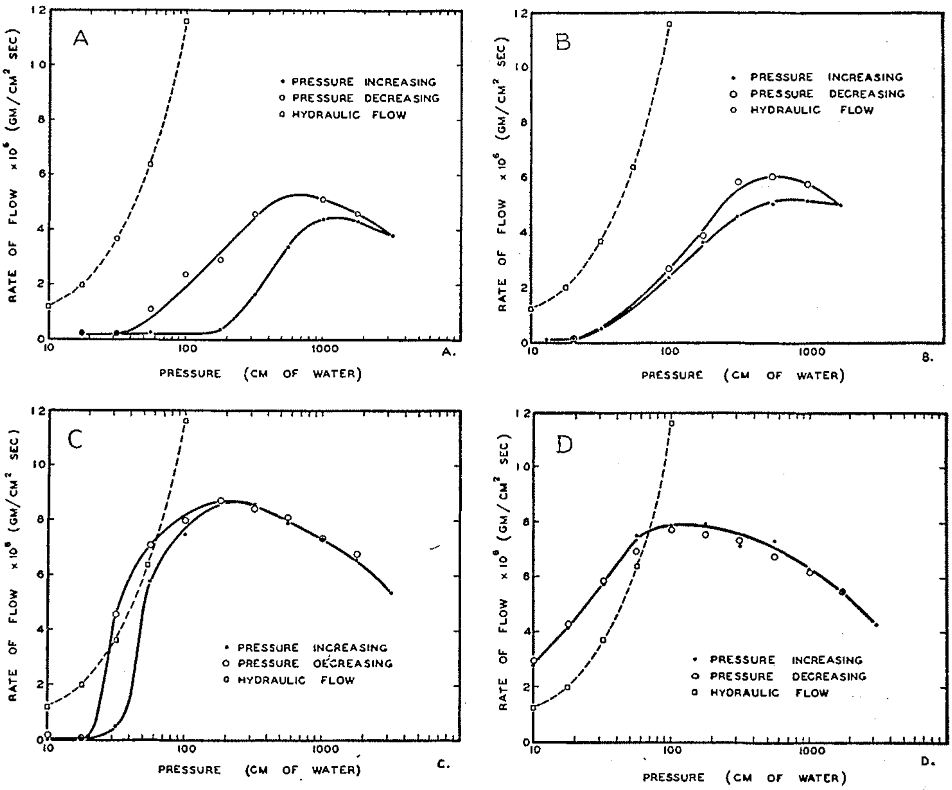

FIG. 3. FLOW DUE TO THE TEMPERATURE GRADIENT WHEN FINE-TEXTURED (*top left*) OR COARSE-TEXTURED (*top right*) SURFACES ARE IN CONTACT *vs.* THE PRESSURE USED TO UNSATURATE THE PORE SYSTEM AT THE INTERFACE; AND WHEN FINE-TEXTURED SURFACES ARE SEPARATED BY 0.0025 cm. (*lower left*) OR 0.119 cm. (*lower right*) SHIMS *vs.* THE PRESSURE USED TO UNSATURATE THIS GAP

curve showing the relationship between the rate of flow through the porous plates and hydraulic head is also shown in these figures.

In each figure, as the pressure increases, the rate of flow increases, passes through a maximum, and then decreases. The maximum flow is smallest for the gap between the fine surfaces in direct contact, larger for the gap between the coarse surfaces, and largest for the gap between the fine surfaces separated by the 0.0025 cm. shims. The maximum for the gap formed by the 0.119 cm. shims is smaller than that for the 0.0025-cm. gap. The pressure at which the maximum occurs is highest in A, figure 3, and decreases from A through D (fig. 3). A, B, and C in figure 3 exhibit a hysteresis.

DISCUSSION OF RESULTS

Since the width of the gap formed by the shims was known, the pressure required to empty the gap could be calculated. The equation used was:

$$r = \frac{\gamma}{P} \tag{2}$$

where

r is the radius of curvature of meniscus (cm.)

γ is the surface tension (dynes/cm.)

P is the pressure (dynes/cm.^{2})

The distance between the plates is 2 r. Table 1 shows the relationship between the pressure and the space between parallel plates that the pressure will empty. From this table, it may be noted that the gap produced by the 0.0025 cm. shims will not empty until a pressure of about 56 cm. of water is applied. Likewise, the lowest pressure used, a pressure of 10 cm. of water, is more than enough to empty the gap produced by the 0.119-cm. shims.

Consider D, figure 3. If there were no temperature gradient across the 0.119-cm. gap, it would empty when a pressure of 10 cm. of water was applied. If now the temperature gradient is applied, vapor distills across the gap and condenses on the surface of the cold plate. Once the vapor has condensed on the cold plate, the pressure of 10 cm. of water, acting as a hydraulic head, causes the liquid to flow through the plate. Two rates are therefore involved: the rate of distillation across the gap and the rate of liquid flow through the plate due to the pressure acting as a hydraulic head.

The curve showing the rate of flow through the porous plate due to a hydraulic head equal to the air pressures used is shown in the figure. The rate of flow at a pressure of 10 cm. of water is seen to be 1.2×10^{-6} g./cm.^{2}sec. By extrapolation, the rate of distillation across the gap at this pressure is about 8×10^{-6} g./cm.^{2}sec. Because of the difference in the two rates, water must have accumulated on the surface of the cold plate. This accumulation would continue until the gap filled to the point where the water probably bridged the gap over a certain area. This reduced the area of the vapor phase and hence reduced the total flow of vapor to the point where the two rates were equal. Experimentally, the two rates were always equal at the steady state, and it is this rate which is plotted in figure 3. At this pressure, therefore, the observed rate is governed by the rate of flow of liquid through the porous plate.

As the pressure is increased up to a pressure of about 70 cm. of water, the observed rate of flow increases, corresponding to the increase in the rate of flow through the porous plates. In the meantime, the rate of distillation decreases in agreement with the known fact that the rate of distillation varies inversely as

TABLE 1

Relationship between pressure and the space between parallel plates that the pressure will empty

Pressure	Distance Between Plates
cm. of water	*cm.*
10.0	0.0146
17.8	0.0082
31.6	0.0046
56.2	0.0026
100.0	0.0015

the pressure in the space above the liquid. At a pressure of about 70 cm. of water, the two rates of flow are equal. Therefore at this pressure the gap becomes empty.

As the pressure increases beyond this value, the gap remains empty and the observed rate of flow decreases, corresponding to the decrease in the rate of distillation, which is now the rate-controlling process. The variation in the observed rate of flow over the entire range of pressures used, therefore, is accounted for.

Theoretically, the portion of the curve to the left of the maximum for the experiment with the temperature gradient across the gap should coincide with the curve showing the flow due to a hydraulic head. The reason for its failure to do so is not known. This peculiar behavior requires further study.

According to calculation, the 0.0025-cm. gap remains saturated as the pressure increases to a value of about 56 cm. of water. At this pressure the gap empties. If the transfer of moisture takes place in the vapor phase, there should be no flow at the pressures at which the gap is saturated and maximum flow at the pressure at which it empties. In general, in agreement with the prediction, *C*, figure 3, shows that there is virtually no flow at pressures below 56 cm. of water and a large flow at 56 cm. That the rate of flow at 56 cm. is not the maximum is again accounted for by the rate of flow through the porous plate being the slower, and therefore, the controlling rate, at this pressure. The further rise and then fall in the observed rate of flow as the pressure increases is accounted for in the same way as for *D*, figure 3.

Because of hysteresis, the moisture content of a given porous sample at any given suction, over a certain range, is higher when the suction is approached from zero suction than when approached from the opposite direction (3, 4). This same hysteresis in the moisture content is shown by the 0.0025-cm. gap, and is reflected by the hysteresis in the rate of flow. *D*, figure 3, shows no hysteresis because the gap is too large to show this effect in this range of pressures.

In *A* and *B*, figure 3, the rate of flow through the porous plates does not enter as a factor influencing the observed rate of flow. The observed rate of flow due to the temperature gradient is much lower at each pressure than the flow through the porous plates. In *A* (fig. 3) for the fine surfaces in contact, the space between the plates is saturated below a pressure of 200 cm. of water and the flow is therefore zero. As the pressure is increased beyond this value, the space is progressively emptied and the rate of flow increases, corresponding to the increase in the area of the vapor phase. At a pressure of 1000 cm. of water, the space is completely empty and the flow is at a maximum. A further increase in pressure produces no further increases in effective area but does reduce the rate of distillation for the reason already mentioned. In *B* (fig. 3) the much larger gap between the coarse surfaces begins to empty at a pressure of 30 cm. of water. Again, the hysteresis shown in *A* and *B* (fig. 3) is due to the hysteresis in moisture content.

When the gap between the plates separated by the shims is emptied, no film flow is possible. On the other hand, when the pore system at the interface of the two plates is emptied, film flow is possible at the points of contact. However, the curves in *A* and *B* (fig. 3) show no characteristic which would indicate appreciable film flow.

Comparing *A*, *B*, *C*, and *D* (fig. 3) the shift of the maximum toward lower pressures occurs because the pressure required to empty a gap decreases as the width of the gap increases. The height of the maximum increases as the texture of the surface becomes coarser because of the increase in area for vapor flow brought about by a reduction in the area of the bearing surface. The maximum is highest when shims are used in agreement with the fact that the area of the bearing surface is at its smallest at this time. That the maximum for the 0.119-cm. gap is less than that for the 0.0025-cm. gap is in agreement with the requirement that, with other factors constant, the rate of distillation decreases with increasing distance between the plates.

The temperature difference across the 0.119-cm. gap was found to be 25 − 24 = 1°C. by thermocouples placed on the plate surfaces. Hence, the rate of distillation across this gap may be calculated, using the equation:

$$W = \frac{MDP}{RTx} \cdot \frac{P_0 - P_c}{P} \qquad (3)$$

where

W is the rate of distillation (gm./cm.^{2}sec.)
M is the molecular weight of water (g./mole)
D is the coefficient of diffusion (cm.^{2}/sec.)
R is the gas constant (ergs/°C. mole)
T is the absolute temperature of the evaporating liquid (°A.)
x is the distance between the evaporating liquid surface and the condensing surface (cm.)
P is the pressure in the space above the liquid (dynes/cm.^{2})
P_o is the saturation vapor pressure of the evaporating liquid (dynes/cm.^{2})
P_c is the saturation vapor pressure at the condensing surface (dynes/cm.^{2})

Substituting the appropriate values in the above equation, the result for a pressure of 100 cm. of water is:

$$W = \frac{18 \times 0.22 \times 83 \times 13.5 \times 980}{8.31 \times 10^7 \times 298 \times 0.119} \cdot \frac{2.375 - 2.238}{83}$$
$$= 2.43 \times 10^{-6} \text{ g./cm.}^2 \text{ sec.}$$

This value is about one-third of the experimental value of 8×10^{-6} g./cm.^{2}sec. at this pressure. This is probably good agreement in view of the uncertainty with which the temperature difference was known. The actual temperature difference was likely larger, in which case the agreement between the calculated and experimental rate would improve.

CONCLUSION

In this system of two porous plates and the gap between them, there was no flow due to the temperature gradient as long as the gap remained saturated.

Flow began when the gap began to unsaturate. The flow attained its maximum when the gap was completely unsaturated. These results are in agreement with the theory that moisture movement due to a temperature gradient across a porous material takes place in the vapor phase.

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