NATIONAL RESEARCH COUNCIL
CANADA

DIVISION OF BUILDING RESEARCH

EFFECT OF TEMPERATURE DISTRIBUTION ON MOISTURE FLOW IN POROUS MATERIALS

BY

W. WOODSIDE AND J. M. KUZMAK

REPRINTED FROM
TRANSACTIONS, AMERICAN GEOPHYSICAL UNION
VOL. 39, NO. 4. AUGUST 1958, P.676 - 680

RESEARCH PAPER NO. 68
OF THE
DIVISION OF BUILDING RESEARCH

OTTAWA

OCTOBER 1958

NRC 4748

PRICE 10 CENTS

Vol. 39, No. 4 TRANSACTIONS, AMERICAN GEOPHYSICAL UNION August 1958

Effect of Temperature Distribution on Moisture Flow in Porous Materials

W. WOODSIDE AND J. M. KUZMAK

Abstract—Several experimenters have observed moisture flow rates through porous materials under a temperature gradient, which are many times the calculated rates based on vapor diffusion. To investigate this discrepancy, a temperature gradient was applied across an enlarged model of a particular, high-quartz wet sand, and the temperature distribution within the pore spaces was measured. For the 'air-dry condition' of the model, the average temperature gradient in the pore spaces was six times the over-all applied gradient. Approximately this same ratio exists, therefore, between the respective vapor pressure gradients.

It is proposed that the flow mechanism consists of multiple vapor diffusion and liquid flow steps in series, the resistance to flow in the liquid phase being negligible, so that the flow rate is determined by the vapor pressure gradients in the pore spaces. The fact that these gradients are of the order of six times the over-all gradient previously used to calculate the flow rate at least partially explains the discrepancy.

Introduction—The mechanism by which water moves through a porous material when subjected to a temperature gradient has not yet been definitely established [*Bouyoucos*, 1915; *Smith*, 1943; *Winterkorn*, 1947; *Gurr* and others, 1952; *Taylor* and *Cavazza*, 1954]. The experimentally observed rate of flow from the hot to the cold side is found to be about ten times the calculated rate based on vapor diffusion [*Bouyoucos*, 1915; *Winterkorn*, 1947; *Taylor* and *Cavazza*, 1954]. It has been suggested that this lack of agreement between the experimental and calculated rate occurs because some of the water flows in the liquid (film) phase [*Winterkorn*, 1947].

Experiments designed to detect this flow in the liquid phase have been carried out in this laboratory. Flow in the liquid phase was not detected [*Kuzmak* and *Sereda*, 1957]. It therefore appears that the flow takes place in the vapor phase. If the flow does take place in the vapor phase, a possible reason for the discrepancy between the observed and calculated rates may be a discrepancy between the true vapor pressure gradient within the pores of the material and the vapor pressure gradient used in making the calculations.

This paper describes an experiment in which the temperature distribution in a model of a porous material was measured. From these measurements, temperature gradients were calculated. The corresponding vapor pressure gradients can also be calculated.

Experimental—The following considerations lead to the design of the model. The moisture in wet sand is presumed to be distributed as thin films on the surfaces of the solid particles, but mainly concentrated in wedge-shaped rings around the points of contact between adjacent particles. Referring to Figure 1, vapor flow may be assumed to occur under a temperature gradient by a process of evaporation in region A, diffusion across the air space, and condensation in region B. In an open system this does not result in a moisture gradient if equal suctions are maintained at the open boundaries. Assuming that the resistance to liquid flow from one side of the water ring A′A to the other is negligible, then the quantity that determines the rate of moisture flow under a temperature gradient is the average vapor pressure gradient in the pore space AB.

One method by which the vapor-pressure gradients in the pore space may be investigated is to determine the temperature distribution in the pore space and on its bounding surfaces since the temperature conditions are the cause of the vapor pressure conditions. A rigorous mathematical approach to the determination of the temperature distribution in such a system appears to be intractable unless simplifying approximations are made. The alternative is to construct an enlarged model of the grain-pore system, impose a temperature gradient upon the model, and measure temperatures at selected locations within the system after establishing thermal equilibrium.

The two extreme packing arrangements of a granular material composed of uniform spherical particles are the open and close packing arrangements. The open packing arrangement, wherein the spheres form a cubic lattice as in Figure 2, was selected for reasons of simplicity. By symmetry the planes through the horizontal full lines perpendicular to the plane of the figure, are all isothermal planes. Similarly the orthogonal planes through the vertical dashed lines are heat flow planes. Thus the temperature distribution in the

N.R.C. 4748

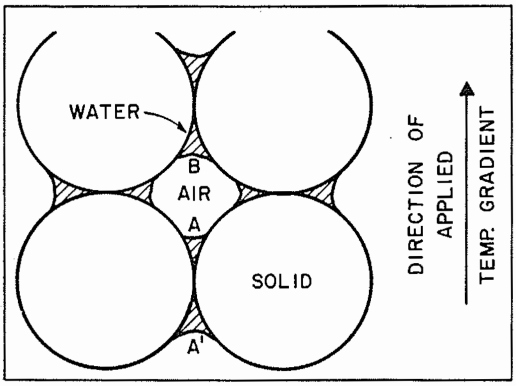

FIG. 1 – Representation of moisture distribution within the pore spaces of a granular material

space enclosed by the heavy full lines is representative of the distribution throughout the material. The model which was constructed is shown in Figure 3, and consisted of four marble hemispheres six inches in diameter, contained in a box, the top and bottom of which was $\frac{3}{8}$ inch aluminum and edges $\frac{1}{8}$ inch lucite.

The temperature distribution in such a system under a temperature gradient will depend upon the relative thermal conductivities of the three constituents, air, water, and solid, as well as upon the configuration or geometry of the system. Let k_a, k_w, and k_s represent the thermal conductivities of the air, water, and solid respectively. In the model the materials must be selected so that the ratios k_w/k_a and k_s/k_a are similar to the corresponding ratios for an actual sand.

The following thermal conductivity values apply to a wet sand of high quartz content at 20°C:

k_s = thermal conductivity of quartz = 20.7 $\times 10^{-3}$ cal/cm sec°C

k_w = thermal conductivity of water = 1.42 $\times 10^{-3}$ cal/cm sec°C

k_a = effective thermal conductivity of saturated air [after *Krischer*, 1941] = 0.238 $\times 10^{-3}$ cal/cm sec°C

The value for k_a is not the thermal conductivity of dry air alone, which at this temperature is 0.0615 $\times 10^{-3}$ cal/cm sec°C, but includes a term which accounts for the latent heat carried by evaporation, diffusion, and condensation of water vapor. By simulating this value of k_a in the model, the effect of evaporation and condensation upon the temperature distribution is taken into account. Thus for a wet sand, $k_w/k_a = 5.96$, and $k_s/k_a = 87.0$.

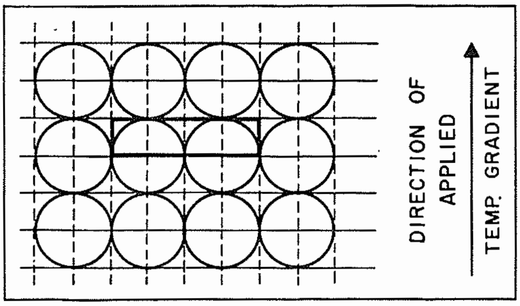

FIG. 2 – Two-dimensional representation of the open-packing arrangement simulated in the model

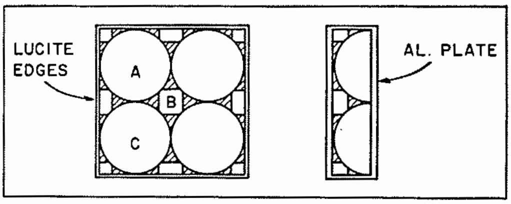

FIG. 3 – The model; A, marble hemispheres; B, silica aerogel; C, bitumen rings

The following materials were used in the model:

(1) Marble was used to represent the solid particles in the model. The four six-inch diameter white marble hemispheres were made spherical to better than $\frac{1}{64}$ inch. Two 8- by 8- by 1-inch slabs of marble were obtained from the same source, so that the thermal conductivity of the marble could be measured in an 8- by 8-inch guarded hot plate apparatus.

(2) Bitumen was chosen to represent the water in the model, since it could be shaped, without too much difficulty, into the wedge-shaped water rings around the points of contact between the solid hemispheres. The thin water films on the particle surfaces were not simulated in the model, since it was thought that they would play a minor role in determining the temperature distribution.

(3) Silica aerogel, rather than air itself, was selected to represent the air in the model to prevent convection.

The following thermal conductivity values apply to the sand model constituents at 20°C:

k_s = thermal conductivity of marble = 4.60 $\times 10^{-3}$ cal/cm sec°C

k_w = thermal conductivity of bitumen = 0.379 $\times 10^{-3}$ cal/cm sec°C

k_a = thermal conductivity of silica aerogel = 0.0576 $\times 10^{-3}$ cal/cm sec°C

Thus in the model $k_s/k_a = 79.6$, and $k_w/k_a = 6.59$ compared with 87.0 and 5.96 respectively in sand. The ratios are therefore the same in sand and model to within 8 and 10 per cent respectively.

Instrumentation and measurements—To determine the temperature distribution in the model 36-gage butt-welded chromel-constantan thermocouples which had previously been calibrated, were installed at selected points in the model. The thermocouples were placed in fine grooves in the marble or bitumen surfaces and held by a thin coat of adhesive. The thermocouples' leads were brought out along the lines of latitude of the hemispheres. Since the lines of latitude are close to being isothermal lines, this method minimizes thermocouple errors caused by heat conduction along the leads.

A temperature gradient was applied across the shorter dimension of the model by installing the model in an 18- by 18-inch guarded hot-plate apparatus. This consists of an electrically heated hot plate and two identical hollow plates (cold plates) cooled by the circulation of constant temperature liquid, and situated one on each side of the hot plate. All plates are 18 inches square. The hot plate is made in two sections, a central 12-inch square test area and an outer 3-inch wide guard ring, which are heated independently and maintained at the same temperature to minimize edge effects. A slab of 18- by 18- by 1-inch fiberboard was placed on one side of the hot plate and the model on the other. The model was installed so that it fitted exactly over the test area of the hot plate. The guard ring section was filled with fiberglass insulating material. With this arrangement, edge effects are negligible, and in addition, measurements on the effective thermal conductivity of the model could be made concurrently.

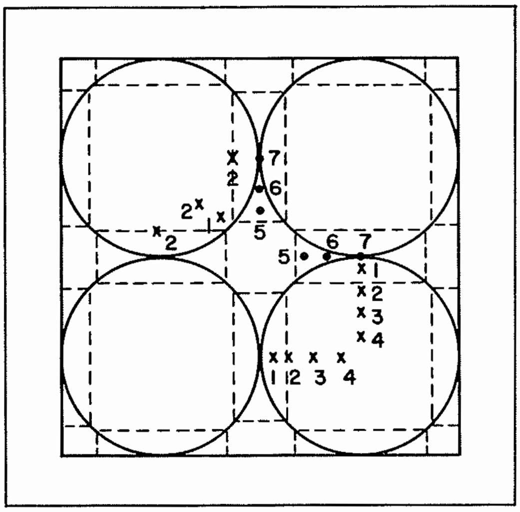

FIG. 4 – Diagram of model showing location of thermocouples; x, on marble surface; ●, on bitumen surface; 1, 2, 3, 4, θ = 30, 45, 60, 75° respectively (on spheres); 5, 6, 7, θ = 30, 60, and 90° respectively (on rings); θ = angle of latitude

The cool face of the model was kept at 55°F by circulating liquid; the hot face was maintained approximately 40°F warmer. Thermal emf's were measured relative to an ice junction with a high-precision potentiometer.

Measurements were made for two simulated 'moisture' conditions of the model. The first represented an air-dry condition, that is, water films on the particle surfaces, but no water rings at the points of contact. Thus for this condition in the model, the entire space not occupied by the marble hemispheres was filled with silica aerogel. The locations of the thermocouples are shown in Figure 4. Measured temperatures at similar positions on the two hemispheres agreed to within one per cent. At the completion of this test, the model was removed from the apparatus, re-installed and the test repeated. Reproducibility was within two per cent.

The second 'moisture' condition simulated in the model represented a moisture content of 26.6 pct by volume of saturation moisture content, or a moisture content of 12.7 pct by volume assuming the porosity to be 0.4764 (actual measured porosity of the model = 0.4711). This 'moisture content' corresponded to bitumen 'water' rings of two-inch radius at the points of contact between hemispheres. No attempt was made to simulate the meniscus curvature of the 'water' rings. The locations of the thermocouples are shown in Figure 4.

Results—From the emf developed by each thermocouple, a temperature corresponding to each thermocouple position was determined. Taking into account the symmetry, the temperature differences between mirror image points separated by the air gap were calculated. The average temperature gradient between any two such points was assumed to be that obtained by dividing the temperature difference by the distance between the points.

The temperature difference between the two isothermal metal plates divided by the distance between them is equal to the over-all gradient. For the different angles of latitude the ratio F of the gradient between mirror image points on the surface of the solid to the over-all gradient was calculated. These are shown in Figure 5a for the

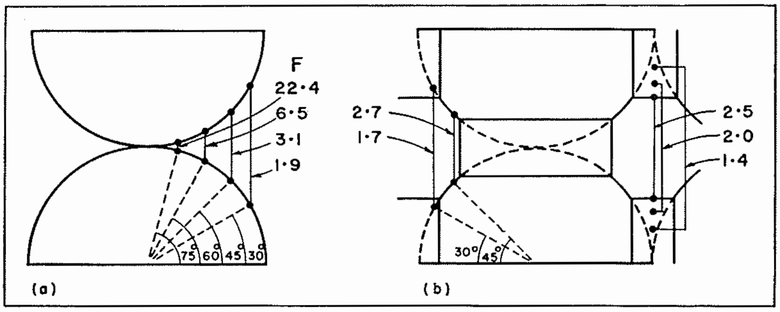

FIG. 5 – Values of the ratio F for (a) the system solid and air; (b) the system solid, air, and water

system solid and air, and in Figure 5b for the system solid, air, and water.

Since the magnitude of F changes with angle of latitude, an average value of F is desirable. Figure 5a shows the value of the factor F at angles of latitude of $\theta = 30, 45, 60$, and 75° for the system solid and air. The value of F at $\theta = 15°$ was interpolated from a graph of F vs θ ($F = 1$ at $\theta = 0$). The average value of F, between $\theta = 7.5°$ and 82.5°, taking account of the slope of spherical surface, and assuming linear flow of heat in the pore spaces, was calculated as

$$\bar{F} = \frac{\frac{\pi}{12}\sum_{i=1}^{5} F_i \cos\theta_i \sin\theta_i}{\int_{\pi/24}^{11\pi/24} \cos\theta \sin\theta \, d\theta} = 6.02$$

where $\theta_i = 15, 30, 45, 60$, and 75°, and F_i are the corresponding values of F. No suitable averaging method could be found for determining $\bar{F}$ for the system solid, air, and water.

Discussion—For the system solid and air, the average value of F is 6, that is, the average temperature gradient across the pore space is six times the over-all gradient. It follows therefore that approximately this same ratio exists between the respective vapor pressure gradients. For the system solid, air, and water, the average value of F was not calculated, but a consideration of the values of F in Figure 5b indicates that the average would be less than six. As the moisture content of the system decreases from 26 pct toward zero, the average value of F will approach 6.

It is therefore proposed that the mechanism of movement involves multiple vapor diffusion and liquid flow steps in series. The resistance to flow in the liquid phase is considered negligible (at least at high relative humidities) so that the rate of moisture transfer is determined by the rate of vapor diffusion. Consequently, if the correct vapor pressure gradient is used in calculating the rate of flow, much better agreement between observed and calculated rates may be expected.

After the completion of the work reported in this paper, a paper by *Philip* and *DeVries* [1957] was brought to the attention of the present authors in which, from theoretical considerations, they arrived at the same general conclusion as reported in this paper regarding the mechanism of moisture flow through a porous material subjected to a temperature gradient. Theoretical values of $\bar{F}$ (denoted by ζ) were tabulated for different porosities and moisture contents. These values ranged between 1.3 and 3.2. If the Philip and DeVries method [*DeVries*, 1952] for calculating $\bar{F}$ is used, a value of 2.04 is obtained for the air-dry condition of the model, compared with the above measured value of 6.02. The Maxwell-Burger-Eucken theory, on which the Philip and DeVries method is based, assumes that the distances between particles are large compared with the particle size. Now, if one makes the approximation that the granular material may be represented by an air layer and a solid layer in series, $\bar{F}$ is found to be 2.09 for the porosity and conductivity ratio used in the model. The fact that the value obtained making this very rough approximation is similar to that calculated by the Philip and DeVries method indicates that the Maxwell-Burger-Eucken theory, because of the assumption concerning the distances between particles, is not applicable to most granular materials.

Acknowledgments—The authors gratefully acknowledge discussions with P. J. Sereda and D. G. Stephenson concerning the design and construction of the model.

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

References

Buyoucos, G. J., Effect of temperature on the movement of water vapor and capillary moisture in soils, *J. Agr. Res.*, **5**, 141–172, 1915.

DeVries, D. A., Het warmtegeleidingsvermogen van grond, *Med. Landbouwhogeschool*, Wageningen, **52**, 1–73, 1952.

Gurr, C. G., T. J. Marshall, and J. T. Hutton, Movement of water in soil due to a temperature gradient, *Soil Sci.*, **74**, 335–345, 1952.

Krischer, O., Warmeleitung und dampdiffusion in Kalteschutzstoffen, *Warme- und Kaltetechnik*, **43** (O), 2–4, 1941.

Kuzmak, J. M., and P. J. Sereda, The mechanism by which water moves through a porous material subjected to a temperature gradient, Part I, The introduction of a vapor gap into a saturated system, *Soil Sci.*, **84**, 291–300, 1957; Part II, Salt tracer and streaming potential to detect flow in the liquid phase, *Soil Sci.*, **84**, 419–422, 1957.

Philip, J. R., and D. A. DeVries, Moisture movement in porous materials under temperature gradients, *Trans. Amer. Geophys. Union*, **38**, 222–232, 1957.

Smith, W. O., Thermal transfer of moisture in soils, *Trans. Amer. Geophys. Union*, **24**, 511–524, 1943.

Taylor, S. A., and L. Cavazza, The movement of soil moisture in response to temperature gradients, *Soil Sci. Soc. Amer. Proc.*, **18**, 351–258, 1954.

Winterkorn, H. F., Fundamental similarities between electro-osmotic and thermo-osmotic phenomena, *Proc. Highway Res. Bd.*, **27**, 443–454, 1947.

Division of Building Research, National Research Council, Ottawa 2, Canada.

(Communicated manuscript received November 25, 1957; open for formal discussion until January 1 1959.)