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HEAT AND MOISTURE TRANSFER IN CLOSED SYSTEMS OF TWO GRANULAR MATERIALS

BY

W. WOODSIDE AND J. B. CLIFFE

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HEAT AND MOISTURE TRANSFER IN CLOSED SYSTEMS OF TWO GRANULAR MATERIALS

W. WOODSIDE AND J. B. CLIFFE

National Research Council, Canada¹

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Many engineering problems require calculations of heat flow through the ground. Such problems as (a) performing a heating load calculation for a basementless house, (b) estimating the heat exchange between the ground and a cold storage building, (c) calculating the current-carrying capacity of buried cables, and (d) determining heat losses from underground steam pipes or hot water lines, require a knowledge of the thermal conductivity of the soil for their solution. Yet, despite the need for accurate thermal conductivity data and the wide use of existing data, the mechanisms by which heat is transferred through soils, especially when moist, are not completely understood. Nor is there agreement as to the most appropriate method by which the soil conductivity should be measured.

In order to understand more clearly the heat transfer mechanisms in moist soils, and also to verify accepted data with similar apparatus, the experiments described herein were performed.

REVIEW OF PREVIOUS WORK

Kersten (5) made a very extensive series of measurements, using a steady-state cylindrical heat flow method, by which he determined the dependence of the thermal conductivity of 19 soils on mean temperature, density, and moisture content. His data are the most widely used at present in making ground heat flow calculations, although it is not known whether these tests were allowed to continue long enough to reach complete steady state. For calculating the thermal conductivity of a soil, Kersten divided soils into two general classes: sandy soils, and silt and clay soils. He summarized his experimental results by the following empirical relationships. For the sandy soils, $M > 1$ and for the silt and clay soils, $M > 7$, for these relationships to be applicable.

¹ Division of Building Research. The senior author is now at Gulf Research and Development Co., Pittsburgh, Pa.; the junior author is at Nova Scotia Technical College, Halifax.

For sandy soils, above 32°F.,

$$k = (0.7 \log M + 0.4) 10^{-0.1D} \quad (1)$$

For sandy soils, below 32°F.,

$$k = (0.011 \times 10^{-0.214D}) + (0.026 \times 10^{-0.146D})M \quad (1a)$$

For silt and clay soils, above 32°F.,

$$k = (0.9 \log M - 0.2) 10^{-0.1D} \quad (2)$$

For silt and clay soils, below 32°F.,

$$k = (.01 \times 10^{-0.214D}) + M(.025 \times 10^{-0.14D}) \quad (2a)$$

where k = thermal conductivity of soil, B.t.u. in./hr. sq. ft.°F.; M = soil moisture content, per cent of dry weight; and D = dry density of soil, lb./cu. ft. Kersten concluded that for most conditions these empirical relationships should enable the calculation of soil thermal conductivities to within 25 per cent.

More recently, transient heat flow methods have been used to determine the thermal properties of soils. De Vries (2) made measurements of the thermal conductivity of sand at different temperatures and moisture contents, using the transient thermal conductivity probe (or "needle") method. The probe method appears to be the most common for the measurement of soil thermal resistivity along proposed buried electric cable routes, since measurements with the probe are fast (testing time about 15 minutes) and may be performed *in situ*.

De Vries (2) also reviewed some of the formulas by which the conductivity of a soil might be estimated from a knowledge of the volume fractions and thermal conductivities of its constituents. An equation derived originally by Maxwell and Lord Rayleigh for the calculation of electrical conductivity, and later used by Eucken (3) for thermal conductivity, was used. For a two-phase medium, for example, dry soil containing solid

particles and air, the equation reads:

$$k = \frac{k_a v_a + k_s v_s F}{v_a + v_s F} \quad (3)$$

where

$$F = \frac{1}{3} \sum_{a,b,c} \frac{1}{1 + (k_s/k_a + 1) g_a} \text{ and } \sum_{a,b,c} g_a = 1$$

k , k_a and k_s are the thermal conductivities of the dry soil, air, and solid particles respectively; v_a is the volume fraction of air (porosity) and v_s the volume fraction of solid particles ($1 - \text{porosity}$) in the soil; g_a , g_b , and g_c are particle shape factors. For example, $g_a = g_b = g_c = \frac{1}{3}$ corresponds to spherical particles. For the application of this equation to dry soils, De Vries selected $g_a = g_b = 0.125$, $g_c = 0.75$, which corresponds to particles having the shape of an ellipsoid of revolution. Equation (3) may also be applied to the calculation of the thermal conductivity of a saturated soil, if for k_a the thermal conductivity of water is substituted, and for v_a the saturation moisture content expressed as a volume fraction. De Vries found that when dry soil thermal conductivities calculated from equation (3) were multiplied by a correction factor of 1.25 they agreed fairly well with the experimental data of Smith and Byers (8) on dry soils.

TRANSFER OF HEAT THROUGH MOIST SOILS

Sand tests

A series of tests was performed on a graded quartz sand having the following properties: soil designation, 20/30 Ottawa sand; particle size range, 0.177 to 0.84 mm.; specific gravity of quartz, 2.58; specific surface, $2.4 \text{ m}^2/\text{g}$. (determined from moisture adsorption isotherm); and "dry cup" water vapor permeability, 21.9 perm. in.

Tests were performed on the sand at a dry density of 100 lb./cu. ft. and at the following moisture contents expressed as a percentage of the dry weight: zero (dry), 2 per cent, 4 per cent, and 24 per cent (saturated).

The apparatus used for these tests was the 12- by 12-inch guarded hot plate (ASTM C177), which is mounted vertically so that the heat flow is in the horizontal direction. The test area of this apparatus, across which the heat flow is metered, is the central 6- by 6-inch square of the hot plate. Thus a square guard ring 3 inches wide

FIG. 1. Variation of thermal conductivity of quartz, water, and dry air with temperature [according to De Vries (2)].

is provided. Two lucite frames of outside dimensions 12 by 12 by 2 inches and of $\frac{1}{8}$ -inch thicknesses were fitted between the hot and cold plates and then filled from the top with the sand specimen, the joints in the assembly being waxed to prevent gain or loss of moisture in the test specimens. A sheet of polythene film was interposed between hot plate surface and specimen to keep the air gap between test area and guard ring free of soil. Cold and hot plate temperatures were maintained at 60° and 90°F., respectively, providing a temperature gradient of 15°F./in. across the sand at a mean temperature of 75°F. The following results and observations are given for each test in turn.

Dry sand. Equilibrium conditions were reached in approximately 60 hours and the thermal conductivity was found to be 1.83 B.t.u. in./hr. sq. ft.°F. Kersten's empirical equation (1) cannot be applied at zero moisture content, but De Vries' equation (3) may be applied. Figure 1 shows the variation of the thermal conductivity of quartz water, and dry air with mean temperature. For sand at 100 lb. cu. ft., the calculated porosity is

0.378. Thus at 75°F. $k_a = 0.18$, $v_a = 0.378$, $k_s = 59$, and $v_s = 0.622$. Using De Vries' values for $g_a = g_b = 0.125$, $g_c = 0.75$, F then equals:

$$F = \frac{1}{3} \left[\frac{2}{1 + 0.125(k_s/k_a - 1)} + \frac{1}{1 + 0.75(k_s/k_a - 1)} \right]$$

With these data, De Vries' equation (3) predicts a thermal conductivity of 1.82 B.t.u. in./hr. sq.ft.°F., which agrees very well with the measured value without a correction factor.

Saturated sand (24 per cent moisture content by weight). The saturated moisture content was based upon the calculated porosity. With 24 per cent water in the sand sample, a free water surface existed at the top, indicating that slightly more water than necessary was present to saturate the sand. It was assumed however, that the sand in the test region of the apparatus was saturated.

Equilibrium conditions were reached in 48 hours, and the thermal conductivity was found to be 19.2 B.t.u. in./hr. sq.ft.°F. Kersten's empirical equation (1) predicts $k = 13.7$ for this density and moisture content. De Vries' equation may be applied as above, except that the thermal conductivity of water is now substituted for k_a ; this results in a conductivity for the saturated sand of 21.8.

From these first two tests it may be seen that saturated sand possesses a conductivity of the order of ten times that of dry sand, and also that De Vries' formula without correction factors predicts conductivities for dry and saturated sand in good agreement with the measured conductivities.

Moist sand (2 per cent moisture content by weight). Equilibrium was reached in 200 hours and the measured thermal conductivity was 3.9 B.t.u. in./hr. sq.ft.°F. Kersten's empirical equation (1) predicts a value of 6.1.

Moisture contents were determined at the completion of the test by the removal of samples in the test region at various space intervals across the thickness of the specimens, and by consequent drying to constant weight. Four samples were removed from each specimen at distances of $\frac{5}{16}$, $\frac{3}{4}$, $1\frac{1}{4}$, and $1\frac{1}{2}$ inches from the hot plate. Each sample had dimensions of $\frac{3}{8}$ inch diameter by approximately $1\frac{1}{2}$ inch long, and since weighings were made on a balance sensitive to

FIG. 2. Equilibrium moisture distribution: initial 2% and 4% moist Ottawa sand; 100 lb./ft.³ dry density; mean temperature, 75°F.; average temperature gradient, 15°F./in., determined by hot plate apparatus.

10^{-4} g., the moisture contents could be determined very accurately. The average equilibrium moisture distribution of the two specimens is shown in figure 2.

It is evident that gravity effects are important even at this low initial moisture content of 2 per cent with an applied temperature gradient of 15°F./in. By drawing the horizontal dashed line at 2 per cent moisture content (fig. 2), the average moisture content in the test region is seen to be less than 2 per cent. Under the action of a temperature gradient, moisture moves from hot to cool regions (4, 7, 9). Thus the moisture content at the cold side probably attained a value large enough to permit gravity drainage out of the test region, leaving an average moisture content in the test region of approximately 1.5 per cent.

Moist sand (4 per cent moisture content by weight). Equilibrium was reached in approximately 170 hours, and the measured thermal conductivity was 7.2 B.t.u. in./hr. sq.ft.°F. Kersten measured a conductivity of 10, while his empirical formula gives $k = 8.2$ B.t.u. in./hr. sq.ft.°F.

At equilibrium, gravity had caused a pronounced observable increase in moisture content

at the bottom of the specimens in the guard ring section. The average equilibrium moisture distribution for the two specimens is plotted on figure 2. The moisture content at the bottom of the specimens was found to be 19.8 per cent, a value approaching the saturation moisture content. Also from figure 2, it is evident that the moisture content in the test region is substantially lower than the initial 4 per cent even at the cold side, the average moisture content being approximately 2.25 per cent. Thus gravity effects were even more pronounced than in the previous test.

An attempt was made to determine the minimum moisture content of the sand at which gravity effects become noticeable. This was done by allowing sand at different initially uniform moisture contents to stand vertically for a considerable time in sealed test tubes. After a 2-month period no gravity effects were observable in a sand column with an initial moisture content of 2.95 per cent, but they were observable at a moisture content of 3.62 per cent. These observations check with the measured cold-side moisture contents in the hot plate tests.

The determination of a thermal conductivity by the conventional vertical guarded hot plate apparatus would seem of little value for a moist material in the moisture content range in which gravity effects are no longer negligible. The measured values will obviously depend upon the temperature difference applied, the thickness of the specimens, and the relative dimensions of the test and guard sections of the apparatus.

EFFECT OF GRAVITY AND TEMPERATURE DIFFERENCE ON MEASURED CONDUCTIVITY

To study in more detail the effect of gravity on the measured thermal conductivity of the sand at 4 per cent moisture content, the 8-inch uniflow apparatus was used. This consists of four 8- by 8-inch plates—two heater plates and two cold plates—mounted horizontally, one above the other, so that the heat flows in the vertical direction. Two identical 1-inch thick specimens of the 4 per cent moisture content sand were installed in the apparatus, in 8- by 8- by 1-inch lucite frames with polythene film covers. The order in which the components of the assembly occur is as follows: bottom cold plate, bottom specimen, bottom heater plate, $\frac{1}{2}$ -in. fiberboard insulation, top heater plate, top specimen, and

FIG. 3. Conductivity of 4% moisture content Ottawa sand at various temperature gradients and heat flow directions determined by 8-inch uniflow apparatus with 1-inch thick specimen; density 102 lb./ft.³, mean temperature 74.5°F.

top cold plate. Constant temperature liquid is circulated through the two cold plates in parallel, and the power input to the heater plates is automatically controlled so that the test areas and guard rings of the two heater plates are all maintained at the same temperature. Consequently, at steady state each of the heater plates produces a heat flow in only one direction (uniflow), that is, downwards through the bottom specimen, and upwards through the top specimen.

Tests were performed with different temperature differences being applied to the specimens. A constant mean temperature was retained, however, in order to study the effect of temperature difference on measured conductivity.

No attempt was made to obtain the equilibrium moisture content distributions in these tests due to the thinness of the specimens.

Tests were performed with temperature differences between hot and cold plates of approximately 10, 20, and 30°F. The results are shown in figure 3.

DISCUSSION

The conductivities measured in the uniflow tests are all higher than the 7.2 B.t.u. in./hr. ft.² °F. measured in the vertical hot plate apparatus at the same initial moisture content. In the horizontal arrangement, all the moisture in the specimens was contributing to the heat transfer in the test region, whereas in the vertical position the test region lost part of its moisture to the bottom guard section.

FIG. 4. Conductivities of Ottawa sand and potter's flint determined by guarded hot plate apparatus; mean temperature, 75°F., temperature gradient 15°F./in.

In all instances a higher measured conductivity was obtained for the top specimen than for the bottom specimen. The difference between the measured conductivity of the top and bottom specimens was 13.1, 17.5, and 22.3 per cent of the mean conductivity at temperature differences of 10, 20, and 30°F., respectively.

The effect of applied temperature difference on measured conductivity is also appreciable, the lower the temperature difference the higher the conductivities obtained. The common point on the curves showing measured conductivity versus temperature difference (fig. 3) was obtained by measuring the slope at the origin of the corresponding heat flow versus temperature gradient curves. This would be the limiting thermal conductivity k toward which the measured conductivity would tend as the applied temperature difference is progressively reduced, and hence represents the thermal conductivity when the moisture is very nearly uniformly distributed. It is this extrapolated conductivity which is plotted in figure 4, showing the variation of k with moisture content for the sand. In the test on the initial 4 per cent moisture content sand, the average equilibrium moisture content in the test region was approximately 2.3 per cent (fig. 2). It is to this equilibrium moisture content that the measured thermal conductivity applies. This correction has been denoted in figure 4 by an arrow, the corrected point being at the point of the arrow. The point (fig. 4) corresponding to the test on the initial 2 per cent moisture content sand has been corrected in a similar fashion.

When a temperature difference is applied to a porous material containing moisture, the moisture is transferred in the direction of hot to cold

by a process of vapor diffusion. If the boundaries of the material are sealed, as in the experiments described, the moisture content must decrease at the hot side and increase at the cold side. A moisture content gradient is therefore set up in the direction of cold to hot, and liquid moisture may be returned to the hot side by capillary forces. Under steady-state conditions, a dynamic equilibrium exists between the two opposing processes, and the moisture is no longer uniformly distributed in the material (4, 7, 9).

If the true thermal conductivity k of a moist material is defined as the conductivity of the material when the moisture is uniformly distributed, then k cannot, in general, be determined by a single steady-state test. What is measured is some sort of average conductivity $\bar{k}$ over a non-uniform moisture content distribution.

The variation of k with moisture content m for the sand (fig. 4) is represented by a convex curve. Thus the rate of increase of k with m is larger at low moisture contents than at high moisture contents (that is, $d^2k/dm^2 < 0$). In a specimen with initially uniform moisture content, the hot region during test loses moisture to the cold region although the total moisture content does not change. The thermal conductivity of the hot region decreases, however, by an amount greater than the increase in conductivity of the cold region. Thus the overall conductivity of the specimen, which is the quantity measured, is less than if the moisture had remained uniformly distributed. This effect becomes greater the greater the moisture redistribution, and therefore explains the observed decrease in measured

conductivity with increasing temperature difference (fig. 3).

This effect also explains the effect of gravity on the measured conductivities in the uniflow tests. In the top specimen, the heat flowed upwards setting up a downward moisture content gradient. Thus gravity assisted the capillary forces in returning liquid moisture to the hot region, producing a more uniform moisture distribution and, therefore, a higher measured conductivity than in the bottom specimen where gravity and capillary forces were opposed.

The effects of gravity and applied temperature difference will be opposite to those just described in the case of a material for which the k versus m curve is concave ($d^2k/dm^2 > 0$).

The results indicate that thermal conductivity measurements by steady-state methods should be performed with as small temperature gradients as possible. (In the ground, natural temperature gradients are generally of the order of 1°F./ft. or smaller, compared with the gradients ranging between 5 and 20°F./in. normally used for laboratory measurements).

CALCULATION OF HEAT TRANSFER DUE TO VAPOR DIFFUSION

It is of interest to make an approximate calculation of the contribution made by water vapor diffusion to the total heat transfer in wet sand. The vapor flux F is given by

$$F = -\mu \frac{dp}{dx}$$

where μ , is the vapor permeability (diffusion coefficient) of the sand and dp/dx is the vapor pressure gradient, which may also be written as

$$dp/dx = \frac{dp}{dT} \frac{dT}{dx}$$

where dT/dx is the temperature gradient. Each unit of mass of diffusing vapor absorbs L units of heat at the evaporation plane and releases it at the condensation plane, L being the latent heat of vaporisation of water. Thus the vapor diffusion acts as a parallel heat transfer mechanism, producing a heat flux Q_v where

$$Q_v = -\mu L \frac{dp}{dx} = -\mu L \frac{dp}{dT} \frac{dT}{dx}$$

But the heat flux Q_v is also given by

$$Q_v = -k_v \frac{dT}{dx}$$

where k_v is the component of thermal conductivity due to vapor flow. Therefore:

$$k_v = \mu L \frac{dp}{dT} \quad (4)$$

The water vapor permeability μ , of the sand was measured by a dry cup technique (1) and found to be 21.9 perm. in. (perm. in. is an abbreviation of the unit: grains in./hr. ft.² in Hg). The dry cup method involves a gravimetric measurement of the steady state water vapor transmission through a layer of the test material under isothermal conditions (73°F.) with a relative humidity of 0 per cent maintained on one side (by means of a dessicant) and a relative humidity of 50 per cent maintained on the other. The moisture content of the sand sample, under the above boundary conditions, was very low, and therefore the vapor permeability measured was probably maximal, since at higher moisture contents, the pore space available for vapor diffusion decreases.

At 75°F. , assuming saturation water vapor pressures in the pore spaces of the wet sand, $dp/dT = 0.030$ in Hg/ $^\circ\text{F.}$ Since $L = 1050$ B.t.u./lb. = 0.15 B.t.u./grain, k_v is given by $k_v = 21.9 \times 0.15 \times 0.03 = 0.10$ B.t.u. in./hr. ft.². $^\circ\text{F.}$

Thus water vapor diffusion makes only a minor contribution to the heat transfer in wet sand.

In general, using Penman's (6) empirical relationship between vapor permeability and porosity P for dry and moist soils

$$\mu = 0.66 P \mu_{\text{air}}$$

the expression for the component of thermal conductivity due to vapor flow becomes

$$k_v = 0.66 P \mu_{\text{air}} L \frac{dp}{dT} \quad (5)$$

where μ_{air} is the diffusion coefficient for water vapor through air. It appears that for most soils, the contribution of vapor diffusion to the total heat transfer is small.

Flint tests

A series of tests was also performed with the 12-inch guarded hot plate apparatus on material described as follows: designation, potter's flint; particle size range, 0.005 to 0.05 mm.; specific gravity of particles (quartz), 2.58; specific surface (from water vapor adsorption), $8.85 \text{ m}^2/\text{g.}$; and "dry cup" water vapor permeability, 29.1 perm. in. This material is not a naturally occurring soil but is a fine white quartz powder similar in particle size to a silt soil.

Tests were performed on this material at the following moisture contents: zero (dry), 10 per cent, 20 per cent, and 35 per cent (saturated). Test conditions were similar to those described for the sand tests in the 12-inch hot plate. It was impossible, however, to maintain the same dry density for all tests. The results are described as follows.

Dry flint. Equilibrium was attained in 100 hours, and the measured conductivity was 0.986 B.t.u. in./hr. sq. ft.°F. at a dry density of 70 lb./cu. ft. The calculated porosity at this density is $v_a = 0.565$ and De Vries' equation (3) gives a conductivity of 0.951 B.t.u. in./hr. sq. ft.°F.

Saturated flint (35 per cent moisture content). The dry density in this test was 82.2 lb./cu. ft., leading to a calculated porosity of $v_a = 0.489$ and hence a calculated saturation moisture content of 37.1 per cent of dry weight. At a moisture content of 35 per cent, however, a free water surface existed at the top of the specimens.

The measured thermal conductivity was 17.0 B.t.u. in./hr. sq. ft.°F., a conductivity of the order of 20 times that of dry flint. Kersten's empirical formula predicts $k = 7.9$, and De Vries' formula predicts $k = 16.9$.

TABLE 1

Comparison between measured and calculated thermal conductivity for dry and saturated conditions

Material	Thermal Conductivity, B.t.u. in./hr. sq. ft. °F.	
	Measured	Calculated
Dry sand.....	1.83	1.82
Saturated sand.....	19.2	21.8
Dry flint.....	0.986	0.951
Saturated flint.....	17.0	16.9

FIG. 5. Equilibrium moisture distribution: initial 10% and 20% moist potter's flint; 70 lb./ft.³ dry density; average temperature gradient, 15°F./in., determined in hot plate apparatus.

The comparison between measured thermal conductivity values and those calculated from De Vries' formula for dry and saturated sand and flint, is shown in table 1. De Vries' formula gives conductivity values in good agreement with the measured values without the application of the correction factor 1.25.

Moist flint (10 per cent moisture content). Equilibrium conditions were reached in 60 hours, and the measured thermal conductivity was 6.01 at a dry density of 65.2 lb./cu. ft. Kersten's empirical formula gives $k = 3.14$. The final moisture distribution is plotted in figure 5.

Moist flint (20 per cent moisture content). Equilibrium was reached in 80 hours, and the measured conductivity was 8.2 at a dry density of 69.5 lb./cu. ft. Kersten's formula gives $k = 4.8$. The equilibrium moisture distribution is shown in figure 5.

Since such a uniform final moisture distribution suggests that capillary effects are occurring across the entire specimen thickness, it cannot be concluded that an applied temperature gradient produces a pronounced moisture content gradient in all enclosed moist granular materials.

Gravity effects were not observed during the flint tests and consequently no tests were performed with the unflow apparatus. A separate

test showed that gravity movement of water would begin at a moisture content of between 25 and 27 per cent. In this material also, vapor diffusion makes only a minor contribution to heat transfer.

The relationship between measured conductivity and moisture content for this material is shown in figure 4.

CONCLUSIONS

(a) De Vries' formula for the thermal conductivity of a dry or saturated soil enabled conductivity values to be calculated that are in good agreement with the measured values for the two materials tested. No correction factor was required.

(b) For the two materials tested thermal conductivity values calculated from Kersten's empirical formulas differ in most cases from the measured values by more than 25 per cent.

(c) The measurement of thermal conductivity by the conventional vertical guarded hot plate (horizontal heat flow) appears to be of limited value for a moist sand in the moisture content range in which gravity effects predominate.

(d) In the case of vertical heat flow in the sand at a moisture content in the range where gravity effects are important, measured conductivities were higher for heat flow upwards than for heat flow downwards, the difference increasing as the applied temperature difference was increased.

(e) The measured thermal conductivity of the sand varied with the applied temperature difference, higher conductivities being obtained the lower the temperature difference.

(f) Water vapor diffusion, with its associated latent heat transfer, contributes only in a minor

way to the total heat transfer in the two materials studied.

(g) Gravity effects were not observed during the tests on potter's flint. Since the steady-state moisture distribution was more uniform than in the sand, it is expected that temperature difference effects would also be less pronounced.

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