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CONTRIBUTION OF ICE MOVEMENT TO HEAT AND MASS TRANSFER PROPERTIES OF POROUS SOLIDS

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The results of experiments are presented for heat and mass transfer through water-saturated ceramics with an ice inclusion. Temperature gradient dependences of heat and mass fluxes are obtained at different average temperatures. Possible reasons are suggested to explain the difference of the experimental data from theoretical prediction.

As water-saturated fine-grained soil freezes up, water is normally driven toward the freezing front and soil moisture increases. Structural changes in freezing soil are especially intense in the frozen part, where the temperature approaches the freezing point, and are accompanied by heat and mass transfer. Ice can move relative to soil particles as a consequence of regelation thus contributing to heat and mass transfer. This motion can be induced by different thermodynamic forces, such as gradients of pressure, temperature, and concentration.

The behavior of cryosols in a gradient temperature field reveals properties that seem to be unexpected. Water in a closed system of a uniform fully saturated frozen soil migrates towards lower temperatures under a temperature gradient about the natural one [*Ershov, 1979*]. In an open system, on the contrary, the mass flux through a soil sample is in the direction of the temperature gradient [*Perfect and Williams, 1980*]. The reason is that the deformability of soil skeleton is crucial in the former case of a closed system (water content changes being impossible otherwise) but is insignificant in the case of an open system while the motion of ice relative to the soil skeleton becomes of major importance.

Both factors should be taken into account in modeling heat and mass transfer in frozen soil. Furthermore, one has to bear in mind that deformation of a soil skeleton is always attendant with motion of ice relative to soil particles.

The problem is in finding the general laws of the relative motion of solid phases in frozen and freezing soils. The sequence of steps in the solution implies that the soil skeleton deformation were excluded from consideration, e.g., by means of using porous materials with a stiff matrix.

In this study we report the results of experiments on heat and mass transfer through ceramics with an ice inclusion under a temperature gradient and compare them with theoretical prediction.

Figure 1, *a* shows the main unit of the experimental device. The sample is a water-saturated ceramic cylinder with a cavity (Fig. 1, *b*).

Before the experiment, the system was vacuumed and filled with distilled water. The experiment was run in conditions of an open system at negative temperatures and a zero pressure difference at the sample boundaries. The cavity in the sample center was filled with ice. The ceramics at the side of the cavity consisted of three rings separated by thin sealant (13). That is why water transport through the middle of the sample was assumed to be by regelation.

The temperature gradient induces water flux in the system. The volumetric water flow rate was measured from motion of meniscus in capillary tubes (7) connected to the cell input and output (Fig. 1). For heat flux measurements, standard cylinders (3) were set tightly against the external bases of brass fins (2); heat transfer was through the cylinders to massive heat-exchangers maintained at a constant temperature (5). Axial heat flux in the cell was estimated, according to the Fourier law, from temperatures measured at the bases of cylinders (3).

A single run took from 18 to 36 hours, the time during which constant temperature was maintained at the heat exchangers. Water flux through the sample was measured likewise for the same period.

Ceramics is a phase barrier that prevents ice from penetrating into vessels (14) for the temperature range 0...–0.05 °C.

In most runs, root mean square deviation from the mean temperature did not exceed 0.0005 °C in the heat exchangers and 0.005 °C in brass fins.

The experimental data were compared with the theory using specially designed software [*Kolunin, 2005*] applied also to solve the associated problems of heat in the interior of the main unit and filtration in ceramics. The input parameters were the temperature of heat exchangers and the pressure in the tubes. The software was used to estimate the velocity of ice mov-

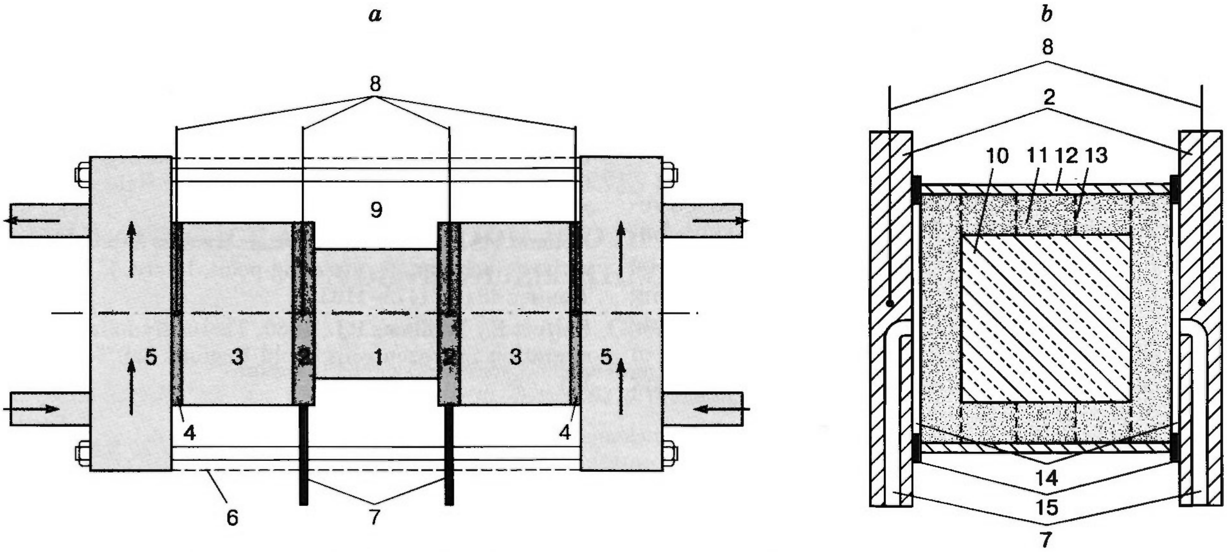

Fig. 1. Layout of the system for investigating heat and mass transfer in porous solids.

a – general layout: 1 – sample, 2 – brass fins, 3 – plexiglass cylinders, 4 – copper plates, 5 – brass heat exchangers which thermostatic liquid is pumped through, 6 – copper foil screen, 7 – water channels, 8 – measuring ends of difference thermocouples, 9 – foam plastic; *b* – measured sample: 10 – cavity (ice), 11 – porous ceramics, 12 – plastic cartridge, 13 – joint of porous ceramic rings, 14 – water-filled clearance vessels, 15 – rubber sealants.

ing in the cavity plane, the temperature of the brass fins, and the fluxes of heat and moisture through the sample bases.

The flux of material through the sample was assumed to be in the direction of the temperature gradient. The heat and water fluxes depended almost linearly on the temperature difference (Fig. 2). As the mean temperature decreased, other things being equal, the fluxes decreased proportionally. Compared with theoretical prediction, the experimental points are below the calculated ones (Fig. 2, *a*, *b*).

The regleation movement of ice in the cell cavity can produce spatially separated heat sources and sinks thus contributing to heat transfer through the cells. The effective thermal conductivity of a cell (λ) depending on ice velocity was predicted to be 1.53 W/(m·K) and decreased nearly by a factor of 1.5 when ice was fixed relative to the ceramics. The average experimental thermal conductivity coefficient was 1.26 W/(m·K) (Fig. 2, *a*), which corresponds to an observed ice velocity about 1.7 times lower than the predicted one. The theoretical ice velocity may be

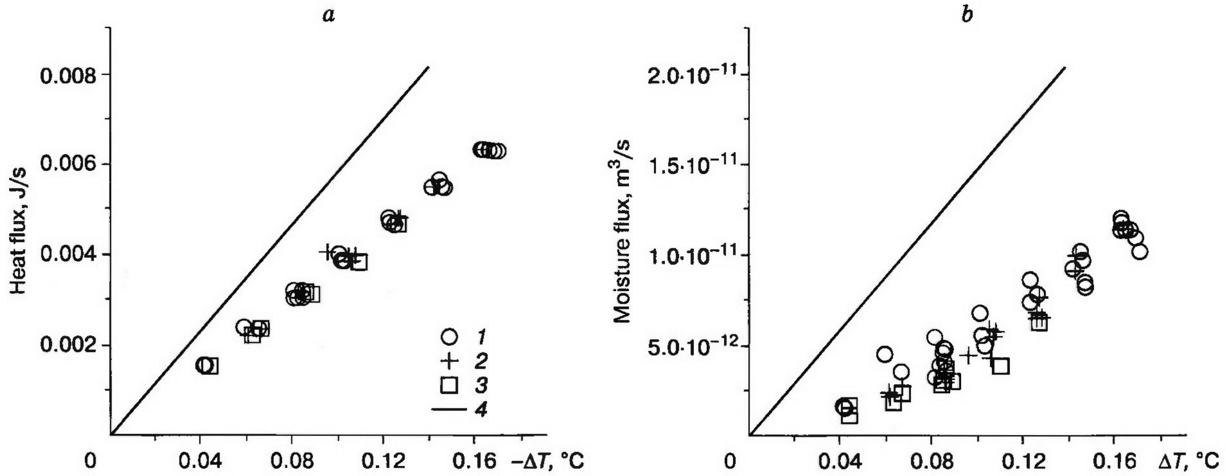

Fig. 2. Heat (*a*) and water (*b*) fluxes through sample as a function of temperature difference ΔT at its base surfaces.

1–3 – experimental data at average temperatures –0.02 °C, –0.03 °C, –0.04 °C, respectively; line is theoretical prediction.

higher because it neglects the resistance of unfrozen water films between the ice and the ceramics in the phase change domain.

The thermal osmotic coefficient calculated from experiment data (Fig. 2, *b*) turned out to be 2–3 times as low as the predicted value.

The difference between real and predicted ice velocities alone cannot account for the disparity between the experiment and the theory. There must be some channels between the domains of ice melting and water freezing that never freeze up and provide liquid phase (water) exchange between the bases of ice cylinders thus decreasing the moisture flux through the sample and, as a consequence, decreasing the thermal osmotic coefficient as well.

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