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Heat and mass transfer through water saturated ceramics with inclusions of ice

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ABSTRACT

The experimental setup is made to study the heat and mass transfer properties of frozen ceramics. Measurements were carried out for two ceramic samples, one of which (sample A) contains an ice body about 5 cm^3, and ice in the other (sample B) is a set of small grains with sizes of 1–100 μm.

The hydroconductivity and thermo-osmosis coefficients of the sample A are several orders higher than the corresponding coefficients of the sample B.

Barothermic effect is registered for only one sample namely the ceramics with the ice macro-inclusion.

The thermal conductivity coefficient of the sample A is a non-monotonic function of temperature, in contrast to the sample B.

Distinctive features of the sample A are associated with the regelation movement of ice in a porous medium under the influence of the temperature and water pressure gradients.

1. Introduction

In the cold regions of Earth is often observed the frost heave phenomenon, i.e. porosity of the unfrozen soil may be considerably increased after freezing [1]. The main reason of it is the liquid movement to the phase transition region during the soil freezing. A set of factors having an influence on the rate of the mass transfer process is estimated by numerous experimental investigations [2,3]. First of all, those are the soil properties as follows: dispersity, mineralogical make-up, and the composition of the exchangeable cations; as well as the features of the system interaction with the environment namely the freezing rate and the hydraulic connection with the water source.

The soil water transforms to ice in a temperature range from −80 to 0 °C [1]. Near the temperature of 0 °C the frozen soil may contain the appreciable amounts of liquid phase. That provides relatively high rate of the mass exchange within the porous medium.

The mass transfer processes in the frozen ground may be initiated besides the thermal gradient another thermodynamical forces such as the gradients of liquid pressure, concentration pore solution, and electrical potential [4].

The heat and mass transfer laws generally represent a functional dependence between the fluxes and the thermodynamical forces. Near the equilibrium state the dependence is the linear form [5]. The transfer coefficients in those relations are found by the experimental methods. Now one property of the frozen soil is most studied namely thermal conducting [6,7]. Fewer experimental results are presented on filtration [8,9], thermo-osmosis [10], and electrical osmosis [11–14].

Measurement of the transfer coefficients takes a long time for which as rule the texture of the frozen soil changed. The texture conversions are accompanied by the movement of liquid relative to the solid components. Therefore the diffusion processes in the frozen soils are described by the effective coefficient diffusion, some contribution to that gives the convective transport of the soluble compounds [15,16].

Sometimes the considered system detects at first sight the unexpected properties. It is known that in closed system the thermal gradient in the homogeneous air-free frozen soil induces the liquid flow towards lower temperature [2]. In open system the opposite picture is observed i.e. mass flow through the sample coincides with the direction of the thermal gradient [10].

In the first system the necessary condition of the mass exchange is deformability of the mineral skeleton otherwise the redistribution of porous space is impossible. In the second system the deformability skeleton plays a secondary role and the main factor becomes movement of ice relative to the soil particles.

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Both of these examples can be explained in terms of the model of the frozen ground as the «soil mass» [17]. However, a number of assumptions of this model requires experimental validation. For example, the heat transfer law does not include the convective component associated with ice regelation, and the fluid flow law is selected in the form of Darcy's law, disregarding the thermo-osmotic properties of the system. The degree of validity of such approximations can be judged after studying heat and mass transfer through a frozen porous medium with the rigid skeleton.

Theoretical study of such systems shows that the laws of heat and mass transfer are to be written in the Onsager form, i.e. the heat and mass fluxes are expressed in terms of the all set of the thermodynamic forces: the gradients of temperature, pressure, concentration and electric potential [18–20]. Experiments with the water saturated ceramics containing the macro-inclusion of ice confirm this conclusion [21,22] but the experimental values of the transfer coefficients differ from the theoretical ones. The measured filtration coefficient turns out two times more found in the theory. And vice versa the experimental non-diagonal coefficients are five times less than the calculated values.

The most likely reason for this difference lies in the fact that the theory neglects the properties of the unfrozen water film between ice and the skeleton of the porous medium. The hydraulic channels between the ice surface and the mineral framework, on the one hand, increase the hydraulic capacity of the medium as a whole and, on the other hand, decrease the pressure drop along the ice inclusion, thereby reducing the absolute value of the non-diagonal transfer coefficients. The importance of these channels in the processes of mass transfer will increase with decreasing size of ice inclusions.

In this connection a question arises about a role of the size factor in the processes of the heat and mass transfer in frozen porous media.

2. Experimental Technique

General view of the experimental setup is shown in Fig. 1. The main unit has a cylindrical shape and its design provides an axial symmetry of the internal temperature field (Fig. 2a). A fully water-saturated porous sample is located in the main unit and connected with a water supply. This paper presents the experimental results of the heat and mass transfer through two samples A and B. (Fig. 2b) containing the ice.

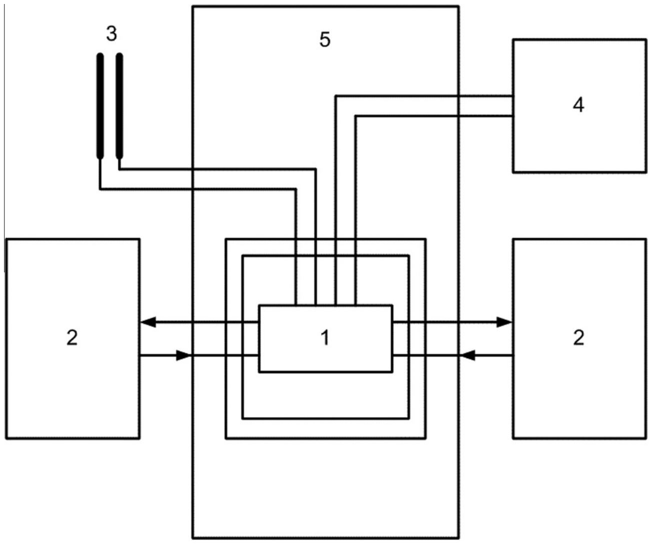

Fig. 1. General view of the experimental setup. 1 – main unit, 2 – liquid thermostat, 3 – capillary tubes, 4 – processing unit of the thermocouple signals, 5 – household refrigerator.

The basic sizes of the setup and characteristics of ceramics are shown in Tables 1 and 2.

The sample A consists of five ceramic plates separated by the thin layers of sealant and has the cylindrical cavity in the middle part. At the negative temperature this volume is filled with ice. Thus it is assumed that the mass flow through the middle section of the sample is transported by the ice inclusion owing to regelation. The volume fraction of ice is 0.28. The ice penetrates through ceramics into the water layer (6, Fig. 2b) at temperature about −0.05 °C.

The inner part of the sample B is made of the same ceramics, what is used in the sample A, and consists of five cylindrical plates enclosed in a plastic holder and limited the fine-pored plates at the ends. The plates served phase barrier against the penetration of ice in the gap (6, Fig. 2b) at temperature down to −0.26 °C. Dependence of the amount of ice on temperature is found by the dilatometric method (Fig. 3). The temperature dependence of the ice–water equilibrium in the confined space [23] allows us to find the minimum size of the ice inclusion in the ceramics at −0.2 °C. It is equal to 1 μm. The maximum size of the ice is determined by the surface irregularity of the ceramic plates (2, Fig. 2b) and does not exceed one tenth of a millimetre.

The preparatory stage of the experience includes following works: evacuating a sample and the water pipes, filling system by the degassed distilled water, unidirectional freezing of the sample, and subsequent melting the ice in the water pipes (7, Fig. 2a) and gaps (6, Fig. 2b).

The heat and mass flows in the main unit are generated by the difference of fluid pressures in the capillary tubes (7) or temperatures between heat exchangers (5). The etalon cylinders (3) are used to determine the magnitude of the heat flux at bases of a sample (1) (Fig. 2a). The fluid flow is determined by the movement of the air–water meniscus in the calibrated capillary tubes (3, Fig. 1). The magnitude of the temperature is measured at four points (8, Fig. 2a) by means of the copper–constantan thermocouples.

The reference junctions of the thermocouples are kept at 0 °C by immersing those in the Dewar flask filled with the distilled water and the crushed ice. In turn the flask is placed in a household refrigerator where the temperature of air is slightly above 0 °C.

Thermal e.m.f. of the thermocouples is measured by the analog-to-digital converter, performed on a chip AD7794, which has six differential inputs. The device operates with resolution 24-bit at 128 gain and an internal 1.17 V reference. Absolute error of the measurement system is not more than 0.01 deg. Error in the measurement of the temperature difference by the differential method is less than 0.004 deg. For most measurements the standard deviation of the mean temperature of the heat exchanger does not exceed 0.0005 deg., the brass plates −0.005 deg. The signal in the digital code is transferred to the computer using the microcontroller and recorded every 10 s.

The Julabo thermostats with a resolution of 0.01 deg. are used for maintaining the temperature of the heat exchangers (5, Fig. 2a).

To create a pressure difference in the pipers (7, Fig. 2a) the water in the input capillary tube (3, Fig. 1) comes from the vessel, what is connected with the compressed-air flask. The water in the output tube is always kept at the atmospheric pressure.

All experimental points are received at steady state conditions. A registration period of one experimental point is approximately 24 h. A time interval between the adjacent experimental points is changed in range 4–7 days.

Hereinafter the results of experiments are presented to display the size effect of ice inclusions on the heat and mass transfer characteristics of the frozen porous materials at steady-state conditions. As the object of the study, two samples are taken, one of