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Thermal energy movement analysis of geotechnical systems

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The process of transferring thermal energy (heat) distributed in nature are largely determined by the practical activities of man. The concept covers the entire range of heat transfer phenomena of heat in space caused by temperature difference Geotechnical individual elements of the system. In general, the heat transfer is a complex process associated with a variety of physical phenomena, but there are three main types (mechanism) heat, thermal conductivity, convective heat transfer and heat radiation. Since these phenomena occur and geotechnical conditions of any level, then they are considered in detail. Heat of geotechnical system is a combination of many different origins thermal fields: natural - geothermal gradient, heat tectonic, magmatic, volcanic and seismic processes, energy and hydrothermal fluid flow, etc. Others - man-made, such as thermal pollution from industrial and mining enterprises, various waste heat process water, underground recycling, gasification and combustion of fuel and others. Given the composition of Geotechnical multiphase system, we have to divide the heat transfer mechanisms in each of its components. The variety of thermal processes instituted mountain range requires additional analysis, parameterization and develop a holistic approach to predicting system behavior and calculation parameters for the purpose of managing its elements in difficult conditions geotechnical systems.
Keywords: geotechnical systems, thermal energy, heat transfer, heat transfer

Аналіз руху теплової енергії геотехнічних систем

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Процеси передачі теплової енергії (теплообмін) поширені в природі і багато в чому визначаються практичною діяльністю людини. Поняття теплообміну охоплює весь комплекс явищ переносу теплоти в просторі, зумовлених різницею температур окремих елементів геотехнічної системи. У загальному випадку перенос теплоти - це складний процес, пов'язаний з різноманітними фізичними явищами, однак можна виділити три основні види (механізму) теплообміну: теплопровідність, конвективний теплообмін і теплообмін випромінюванням. Оскільки, усі ці явища мають місце і в умовах геотехнічних систем будь-якого рівня, далі вони розглянуті докладніше. Теплова енергія геотехнічнічної системи являє собою сукупність багатьох термічних полів різного походження: природних – геотермічний градієнт, теплова енергія тектонічних, магматичних, вулканічних та сейсмічних процесів, енергія гідротермальних та флюїдних потоків, тощо; інші – антропогенних, наприклад, теплове забруднення від промислових та видобувних підприємств, різні відходи, теплі технологічні води, підземна переробка, газифікація і спалювання палива та ін. З огляду на багатофазний склад геотехнічної системи, необхідно розділяти механізми передачі теплоти в кожному з її компонентів. Різноманіття термічних процесів у порушеному гірському масиві потребує додаткового аналізу, параметризації та розробки цілісного підходу до прогнозування поведінки системи та розрахунку параметрів, з ціллю управління її елементами в складних умовах геотехнічних систем.
Ключові слова: геотехнічна система, теплова енергія, теплопровідність, теплообмін

Introduction. The thermal energy of a geotechnical system is a composition of many thermal fields of different origin (fig.1)

Some of them are natural – geothermal gradient, thermal energy of tectonic, magmatic, volcanic and seismic processes, energy of hydrothermal and fluid currents, etc, others – anthropogenic, like for example, thermal pollution by industrial and extractive factories, different wastes, thermal technical water, underground processing, gasification and burning fuel, etc.

Considering the multi-phase compound of geotechnical systems, the mechanisms of heat transfer should be defined for each of its components. The variety of thermal processes in a disrupted rock massif requires additional analysis, parameterization

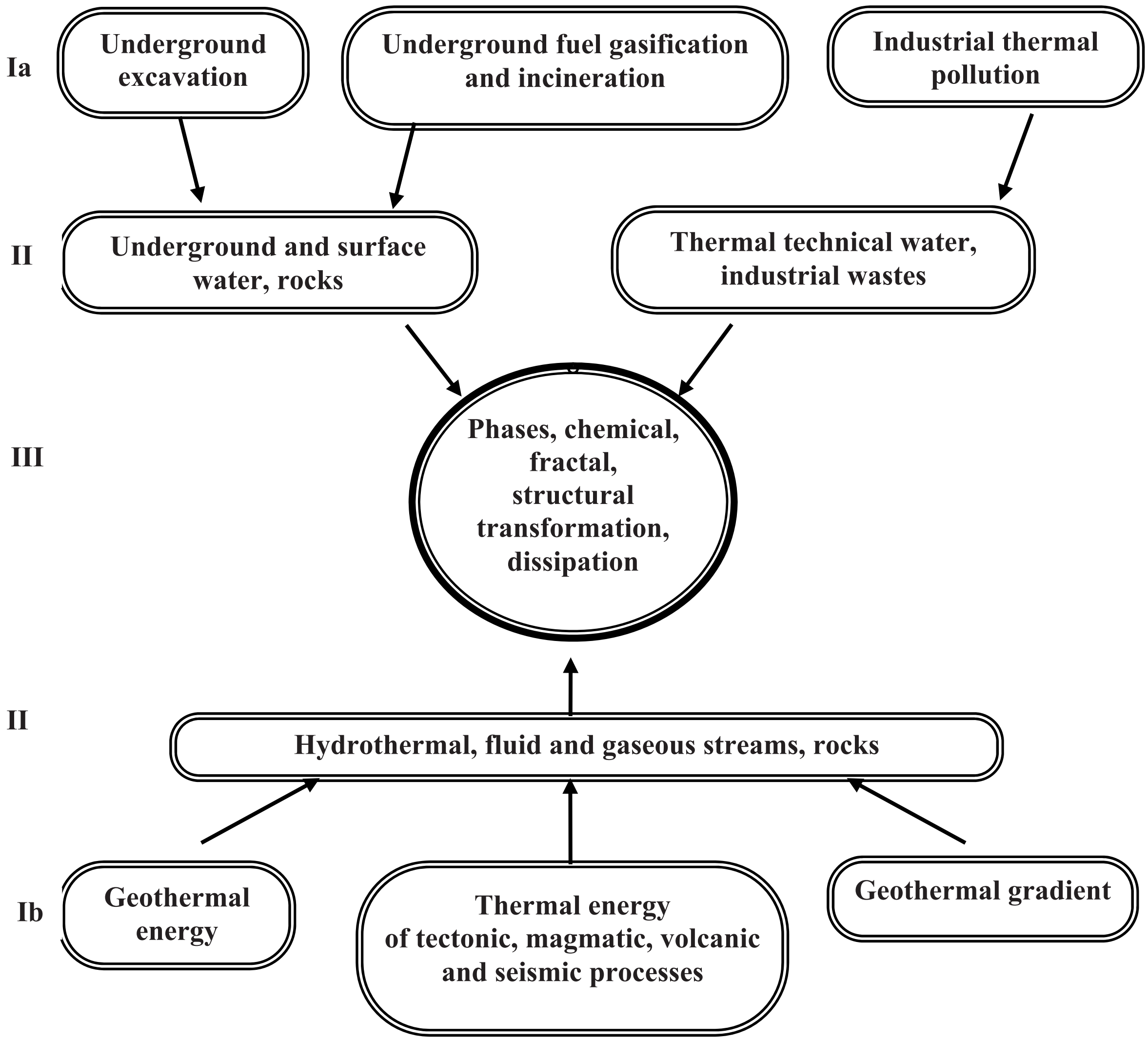

Fig. 1. Thermal scheme of a geotechnical system: Ia and Ib – the sources of thermal energy, anthropogenic and natural, respectively; II – the paths of thermal energy transfer; III – the conversions of thermal energy in a geotechnical system.

and development of a complex approach to predicting the system`s behavior and estimating parameters for managing its elements in the complex conditions of a geotechnical system.

Scheme 2 partly shows a great number of thermal balance factors in a geotechnical system, their direction, influence and interaction, but it provides sufficient material for primary research into representing the complex system complicity of disruptions in rock massifs.

Presentation of the general material. Heat transfer is molecular transfer of heat in bodies (or between the bodies), caused by non-uniformity of temperature in the considered space. It is not related to macro movement of bodies and is performed by transferring energy from the small particles of a body to other small particles during their interaction.

The process of heat transfer in massifs, as in a thick component of a geotechnical system, is similar to the process of electrical conduction and is related to the movement of free electrons. In the simplest case, free electrons can be considered moving between atoms and perform transfer of thermal energy. Therefore, the process of heat transfer is defined by the diffusion of free electrons.

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A heat transfer made by a rare component of a geotechnical system, i.e. mostly by ground water in different forms, is made by flexible waves. For the

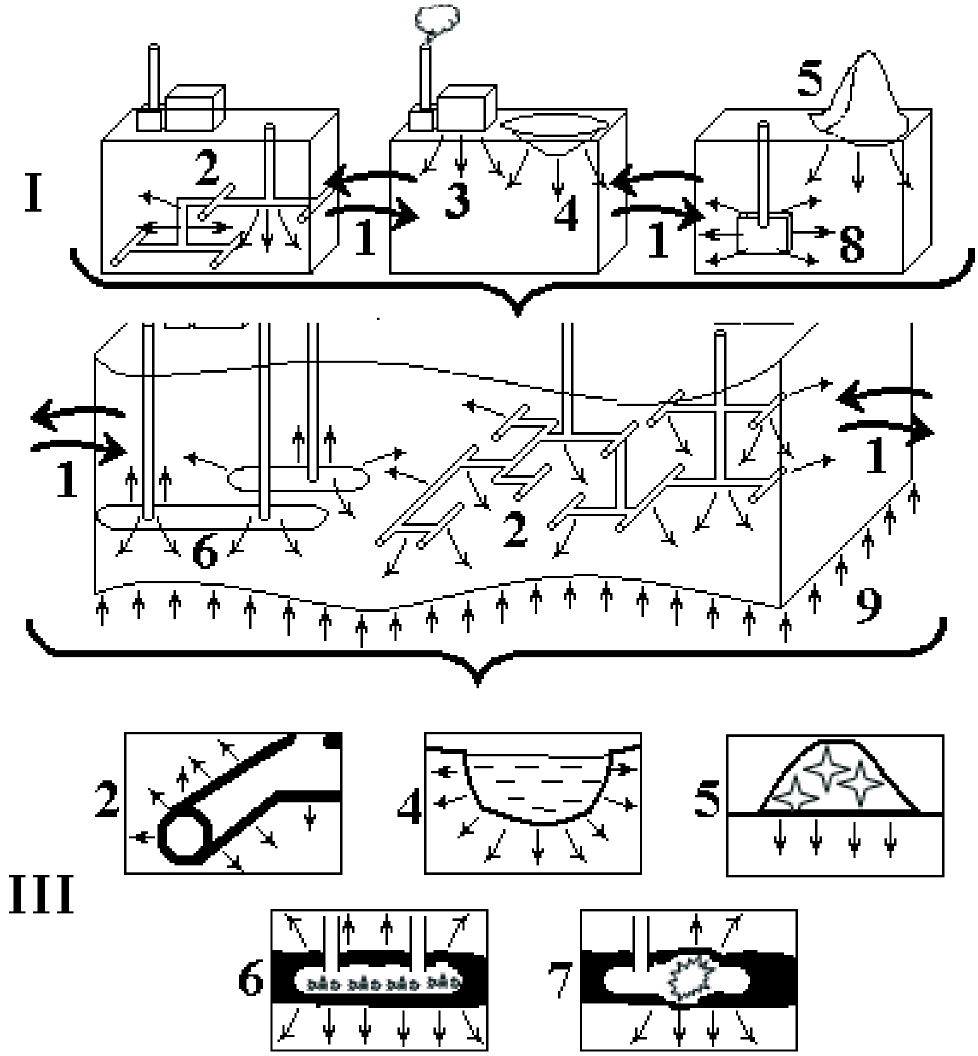

Fig. 2. Schematization of thermal transfer processes in different geotechnical systems:

I, II, III – different scales of the system, macro-, midi- and micro-, 1 – heat exchange between different systems, 2 – underground mining, 3 – industrial thermal pollution, 4 – release of technical water, 5 – terricones and landfills, 6 – underground coal gasification and incineration, 7 – underground industrial (nuclear) explosions, 8 – underground storages of industrial wastes, 9 – thermal flow from subsoil.

gas held in the system, it takes place via molecules. Molecules of the heated part of the gas have more kinetic energy compared to molecules of the cold part. When they collide, an exchange of kinetic energy takes place, i.e. the heated part provides heat to the cold part.

The second type of heat transfer – convection, is connected with movement of a volume of fluid (gas). Convection is possible only in a fluid environment, and the process of heat transfer is inextricably related to transfer of the environment itself. In fluids, heat transfer is always followed by heat conductivity. Heat exchange between a fluid (gas) and the surface of thick body is called convective heat exchange.

The third type of thermal energy transfer – thermal emission, i.e. the process of distributing heat by electromagnetic waves. This type of transfer involves conversion of a substance`s internal energy into energy of emission, transferring the emission and its absorption by the substance.

Thermal emission is caused only by the temperature and optic capacities of emitting body. It is regulated by the basic laws of optics. Pure (i.e. without involvement of other forms of heat transfer) heat emission can take place only in a high vacuum. In the processes which are seen in geotechnical conditions, beam heat transfer comes with convection and heat conductivity. In this case, the heat transfer is called radioactive-convectional. The mathematical study of it is complicated, so often previously each type of heat transfer was studied separately, and then assessment of the combined heat transfer followed. Also, in particular cases, one type of heat transfer dominates, so the amount of heat transferred by other types of heat transfer is insignificant, and therefore can be neglected.

Let us consider the process of heat transfer by heat conductivity in more details. Pure heat conductivity occurs only in solids. In fluids and gases heat is transferred by convection, i.e. pure heat conductivity is possible only if they are absolutely motionless and if there is no possibility of occurrence of convectional flow.

Theoretical study of heat transfer should necessarily consider the environment, where the heat transfer takes place. All bodies which heat conductivity is studied will be conventionally considered solid, i.e. their discreet structure will be neglected. Such approach to studying process of heat transfer in general and heat conductivity in particular, among other cases, is proved reasonable when the sizes of the studied objects are rather large in comparison with distances of effective intermolecular interaction.

We will further consider only uniform solid environments, which have the same capacities at all points with the same indices of temperature and pressure. The isotopic and anisotropic environments are considered. Physical capacities of the first environment does not depend upon the direction, with the second, on the contrary, some capacities at a point can be a function of direction. Geotechnical systems most commonly have isotropic bodies.

Also, as the term "solid environment", we consider not only pure substances, but also their compositions and mixtures (gas mixtures, resolutions, etc). The heat transfer in mixtures of different substances is related to the transferring mass and in a general case is defined not only by the gradient of temperatures, but also by non-uniformity of distributing fields of other physical quantities. For example, non-uniformity of a concentration field leads to diffusion of a substance and additional molecular heat transfer, which is called diffusional heat conductivity (Dufour effect). Usually heat transfer caused by such effects is small and can be neglected.

For the reason that any physical phenomenon occurs in space and in time, its study involves finding the spatial-temporal characteristics of the quantities which define the process. The total of momentary meanings of a physical quantity at all points of its considered part is termed the field of the physical quantity.

The main physical quantity in processes of heat conductivity is temperature and the objective of heat conductivity theory is to define the temperature fields of a considered object.

The temperature is a scalar quantity; therefore the temperature field is also a scalar quantity. We emphasize that abovementioned definition of the field is reasonable for vector magnitudes which show the amount and the direction (power, velocity, acceleration, etc.). Such fields are called vector fields of physical quantities, there are stationary and non-stationary temperature fields.

The non-stationary temperature field is the field whose temperature changes in space and in time, i.e. temperature is a function of space and time. A stationary temperature field is considered to be a field whose temperature at any point is unchangeable over time, i.e. the function of coordinates. Heat regimes which characterize non-stationary temperature fields are termed unsteady regimes. In a case where temperature fields are stationary the heat regime is termed steady.

Depending upon the number of spatial coordinates which the temperature depends upon, the temperature field can be three, two- or univariate. For many provided heat conductivities it is better to use the curvilinear coordinate system than to use Cartesian coordinates.

The transfer from one point to another is followed by some change in temperature. If an infinitely small increase in the spatial coordinates corresponds to infinitesimal changes in temperature, the temperature field is termed continuous [uninterrupted]. In other cases, the temperature field is termed a split temperature field. For a continuous temperature field, the temperature derivative in any direction has a terminating magnitude. From this point we will confine our attention to continuous temperature fields.

If we connect to points of a body, which have the same temperature, we will obtain isothermal surface of different temperatures. Isothermal surfaces are surfaces of temperature field level. If a temperature field is continuous, isothermal surfaces and isothermal lines for these temperatures do not intersect with each other and do not interrupt inside the field.

Heat transfer by conductivity within a body can occur only if its temperature is non-uniformly distributed i.e. a necessary condition for heat flow occurring within a body is a temperature gradient, different from zero. The experience proves that the heat is transferred from points with the highest temperature to points with a lower temperature, therefore heat flow, unlike the temperature, which is a scalar magnitude, has a certain direction.

According to Fourier`s law, heat flow through an element of isothermal surface is defined by the value of thermal gradient at a considered point. Fourier`s main law of heat conductivity is formulated as follows – density of heat flow is directly proportional to temperature gradient.

Heat conductivity is a physical parameter, and in general cases depends upon the temperature, pressure and capacities of a substance. It quantitatively equals the amount of heat that passes in one unit time through unit isothermal surface with gradient temperature which equals one, i.e. when temperature differential is one degree per unit length of normal.

Heat conductivity of different substances varies within a wide range. For gases and vapors, the values are low, but they rise with rise in the temperature. Change of pressure practically does not affect the heat conductivity of gases, except at very high and very low pressures. The heat conductivity of solids is significantly dependent upon the temperature and the character of changes, to a large extent; this is determined by the chemical composition of a substance and its structure. This is especially relevant for mountain rocks, for their heat conductivity along with temperature is also affected by porosity. This is explained by the fact that heat conductivity of pores filled with gas is much lower than the conductivity of solid phase, for the groundwater the reverse is the case. Thus, heat conductivity of rocks is quite dependent upon moisture. Also one cannot neglect the anisotropy of layered thicknesses, where heat conductivity through the layering can differ from the transverse heat conductivity across by 3-4 times.

Convectional heat transfer is a transfer of heat by movement of fluid or gas. It is always followed by heat conductivity, which is why one of the problems in solving the problems of convectional heat transfer is the calculation of the effect of either of heat transfer mechanism. Defining the contribution of heat conductivity and convection to the general process of heat transfer, to a large extent, is simplified by the structure of the research process mathematical model.

Convection heat emission (heat transfer) is a heat exchange between the surface of a solid and a fluid. The calculation of the heat transfer process is based upon the ratio according to Newton-Richmann law, which states that the heat flow from a fluid to a body`s surface element is directly proportional to the element`s area and temperature difference between the body`s surface and the temperature of the fluid. Temperature difference is called temperature driving force, and the body`s surface, through which the transfers takes place, is called the surface of heat exchange or heat transfer surface.

This allows us to define the heat transfer coefficient as density of heat flow to gradient of fluid (gas) and the solid, considered as a difference between the temperature of the body`s surface and temperature of the environment.

In a general case the coefficient of heat transfer is affected by geometrical sizes and shape of a body, the temperature of its surface, the nature of development and regime of fluid movement, velocity, temperature, physical parameters of fluid and many other factors. The heat transfer coefficient can be different at different points of the surface, therefore the average coefficient on the heat exchange surface and local coefficient of heat transfer are considered. To simplify heat calculations the average coefficient on the surface of heat transfer is used.

Heat transfer can involve both types of movement of a fluid phase: free and forced. Free movement occurs as a result of difference between density of heated and cold particles of a fluid, which are in the field of gravity influence. Heat transfer within such movement of the fluid is called free (natural) convection. Forced movement (forced convection) is caused by external factors (e.g. pump, ventilator, wind, etc).

The intensity of free movement depends upon the type of fluid, difference in temperatures of separate particles of the fluid, volume of the space in which the process occurs.

Forced convection in a general case can be followed by free convection. Such heat transfer is called mixed convection. It is easy to see that aperture influence of free convection rises with decrease in velocity of forced movement and, conversely, that the influence of free convection decreases with higher velocities of forced moves.

The heat transfer process is greatly affected by the regime of a fluid`s movement. It defines the mechanism of heat transfer. In a laminar regime, the heat transfer to the body surface (or from the surface) is performed by heat conductivity and is defined by the coefficient of fluid heat conductivity. Because the heat conductivity of fluids (gases) is small, the distribution of heat on the entire mass of the fluid in a laminar regime is very slow. In the turbulent regime, the heat transfer in the direction normal to the body surface is performed both by heat conductivity and by convection. The intensity of heat transfer in a turbulent regime of fluid movement is several thousand times higher than in a laminar regime.

It should be mentioned that in a turbulent regime not all the mass of the fluid has a disordered (chaotic) character of movement. The surface of thick wall always has a layer of fluid, which maintains a laminar character due to viscosity of the fluid.

Another significant factor is change of a fluid`s density with temperature, which is characterized by temperature coefficient of cubic expansion. For theoretical calculations, linear dependencies of a fluid`s density on the temperature are used. The heat exchange is affected also by fluid compressibility, which is characterized by coefficient of pressure (isothermal compression). The values of dropping liquids are very low; therefore they can be neglected during estimations.

Real fluids have viscosity. Between the layers which move with different velocity the power of internal friction (shear force) always occurs and prevents movement. The power of friction between the layers is considered a unit surface and, correspondingly to the Newton`s law, is proportional to the velocity gradient on the normal towards the fluid`s flow. Viscosity of dropping liquids practically does not depend on the pressure and changes with rise of temperature. Viscosity of gases increases with rise in the temperature. The viscosity coefficient of ideal gases does not depend on the pressure.

Thus, the process of convectional heat exchange is characterized by composition of hydrodynamic and thermal phenomena and can be described by a system of differential equations. This is the base for mathematical modeling.

In a general case, the study of convective heat transfer processes leads to defining functional dependencies between variables, which characterize the process. Defining the relation between general physical parameters which define the research process for heat transfer, is rather complicated. This is explained by the fact that temperature fields in convective heat exchange are closely interrelated to velocities. On one hand, temperature field of the fluid which moves in many aspects is defined by the dynamics of flow, i.e. depends upon the field of velocities and its changes. On the other hand, thermal physical capacities of a fluid (first of all, viscosity) significantly depend from the temperature, which itself causes a change in velocity field.

Conclusions. Convective heat transfer is described using general laws of conservation of mass, momentum and energy. Conservation laws are used for distinguishing the elementary volume through the border of which a certain mass, amount of movement and energy which change inside this volume, are transferred within a short period of time. Integration of differential equations composed in such way allows one to define the relation between the required magnitudes for the entire integration area and for the considered period of time.

Because heat transfer in fluids is considered as a continuous medium, the theoretical study of convective heat exchange leads to defining of the relations for the field of velocity, pressure, temperature and physical capacities.

Basic differential equations which describe the process of convective heat exchange are withdrawn from generalized equation of substation transfer, which defines the transfer of mass, impulse, energy, etc., in a continuous medium, which is in motion.

Moreover, for full certainty in solving problems of convectional heat exchange, the system of differential equations requires supplementation with terms of uniqueness. These conditions provide a mathematical description of all peculiarities of the research process. Conditions of uniqueness include: 1) geometrical, which characterize the shape and sizes of an area in which the studied process of heat exchange occurs; 2) physical, which characterize thermal physical capacities of environment and the body; 3) initial, which characterize the process in the initial moment of time (if the process is stationary, these conditions are not considered): 4) boundary, which characterize the peculiarities of the process on the boundary of the area [8]. Thus, mathematical description of convective heat exchange process consists of equations of movement, continuity, energy, heat exchange and the terms of uniqueness. For a large number of cases, the system uses additional correlations (equations of state, etc.).

References

Belyaev N.M., 1989. Osnovy teploperedachy [Fundamentals of heat transfer]. High school publishing, Kyiv. 344 p. (In Russian).

Belyaev N.M., 1987. Thermodinamica [Thermodynamics]. High school publishing, Kyiv. 344 p. (In Russian).

Belyaev N. M., Ryadno A.A., 1992. Matematicheskie metodi teploprovodnosti [Mathematical methods of heat conductivity]. High school publishing, Kyiv. 415 p. (In Russian).

Butuzova L.F. (Eds), 1985. Rol vody v processah termicheskoy i thermookislitelnoy destrukciyi. Geothecnologicheskie problemy toplivno-energeticheskih resursov Ukrainy [The role of wa-

ter in processes of thermal and thermo-oxidative degradation / Geotechnological problems of fuel and energy resources in Ukraine]. Naukova Dumka publishing, Kyiv. 107-113. (In Russian).
Haidai K.O., Zholudiev S. V., 2011. Analiz ruhu teplovoy energiyi v geotehnichnih sistemah [Analysis of thermal energy movement in geotechnical systems]. Bulletin of Dnepropetrovsk National University: Geology - Geography, 13, 96-102. (in Ukraine).
Intersoll L.R., Zobel O.J., Intersoll A.K., 1959. Teploprovodnost, yeyo primenenie v tehnike I geologii [Thermal conductivity and its application in engineering and geology]. Publishing of physical and math literature. Moscow. 259 p. (in Russian).
Leibenzon L.S., 1953. Sobranie trudov. Podzemnaya gidrogazodinamica [Collected Works. The underground fluid dynamics]: Publishing of USSR Science Academy, Moscow. 544 p. (in Russian).
Shchukin L.N. (Eds), 1986. Hydrodinamica i teploobmen v odno i dvuhphaznih potokah [Hydrodynamics and heat exchange in the one- and two-phase flows]. Bulletin of Moscow Energy Institute, 131. Moscow. 162 p. (In Russian).
Vargaftik N.B., 1963. Spravochnick teplophizicheskih svoystv gazov i zhidkostey [Handbook of thermo physical properties of gases and liquids]. Publishing of physical and math literature. Moscow. 708 p. (in Russian).

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