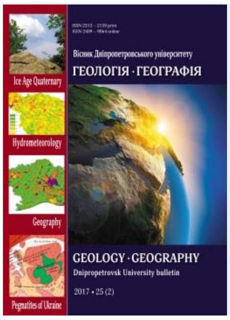

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Research into ground water parameters on the territory of high-temperature industrial enterprises

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Abstract. One of the problems of hydrogeological research is the lack of study of the factors of development and patterns of interaction between the impact and the intensity of technogenic load sources of different character and hydrogeological objects, i.e. absence of data on cause-and-effect relationships in the hydrogeological system. This can be related to insufficient initial information on natural conditions and insufficient study of their possible changes in the course of their exploitation.

In the conditions prevailing today conducting continuous study of ground water seepage conditions on the territories of industrial enterprises is practically impossible. The characteristics of the conditions are determined discreetly, with further interpolation, extrapolation and blending, the research is strongly influenced by the experience and intuition of the researchers. Also, insufficient information on technogenic conditions (existing and projected) and their possible changes during operation of industrial enterprises (dynamics of usage of water from water lines, character of changes in the conditions of surface flow, temperature conditions, etc.) adds to the difficulty.

The aim of this study is to determine the peculiarities of using methods of hydrogeological studies on the territories of industrial enterprises and to conduct an approximate calculation of certain hydrodynamic and hydraulic parameters of groundwater using these methods.

Keywords: underground water, intermediate rolling coolant, heat, Stephen's task, industrial enterprise .

Дослідження параметрів підземних вод на територіях високотемпературних промислових підприємств

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Резюме. До проблем гідрогеологічних досліджень можна віднести недостатню вивченість факторів формування та закономірностей взаємодії численних і різних за характером впливу та інтенсивністю джерел техногенного навантаження з гідрогеологічними об'єктами, тобто відсутність даних про причинно-наслідковий взаємозв'язок у гідрогеологічній системі. Ця невизначеність може бути пов'язана з неповнотою первинної інформації відносно природних умов та недостатньою вивченістю їх можливих змін у процесі експлуатації.

На сучасному рівні забудованості територій досить складно виконати всі традиційні етапи гідрогеологічних робіт. Тому необхідно досліджувати геофільтраційні процеси навколо територій металургійних підприємств для виявлення можливості змін геофільтраційних умов за досліджуваний період у за заданих природних і техногенних умовах (існуючих чи проектних). При цьому визначають межі змін середніх показників об'єкта прогнозування.

Наразі практично неможливо провести безперервні дослідження геофільтраційних умов промислових територій. Їх характеристики визначають дискретно, із подальшою інтерполяцією, екстраполяцією й усередненням, здійснення яких суттєво залежить від досвіду та інтуїції дослідників. Крім того, негативно впливає неповнота інформації щодо техногенних умов (існуючих та проектних) і можливих їх змін у ході експлуатації промислових об'єктів (динаміка втрат із водних комунікацій, характер змін умов поверхневого стоку, температурних умов тощо).

Мета дослідження – з'ясувати особливості застосування методів гідрогеологічних досліджень на територіях промислових підприємств і провести приблизний розрахунок деяких гідродинамічних та гідравлічних параметрів підземних вод за цими методами.

Ключові слова: підземні води, проміжний рухомий теплоносій, теплова енергія, задача Стефана, промислове підприємство.

Introduction. When making a hydraulic forecast, the territory of an industrial enterprise should be considered first of all as a part of open (i.e. with interaction of its separate components) natural-technical system, which consists of two subsystems – the geological environment and the technogenic conditions, which could be divided into the systems of a lower order.

It should be mentioned that because the high density of buildings occupying any industrial site today, it is rather difficult to carry out all the traditional stages of hydrogeological work. Therefore, the research should consider the potential possibility of change in groundwater seepage conditions during the studied period under the given natural and technogenic conditions (existing or projected) by studying the groundwater seepage processes in the territories surrounding the metallurgical enterprise. The process of study includes calculating the boundaries of changes in the given average indicators of the object of forecast.

The existing numerical-analytical and numerical methods are determined; they provide sufficient accuracy of prognoses in the cases with determined groundwater seepage parameters of the environment and hydrodynamic conditions at the borders of water-bearing horizons, and also the functional relation between the forecast values and spatial and time coordinates (E. S. Dzektser, Y. E. Myronov, 1986, Y. A. Rozanov, 1979).

Because in most cases the initial information on natural and technogenic conditions in the studied territories is incomplete, the accuracy of prognoses made using deterministic models decreases. Such peculiarities can be considered using stochastic methods of forecasting, during the consideration of a number of deterministic problems, each corresponding to a certain number of implementations of possible variants (M. V. Bolgov at all, 1998). For considering the stochastic character of hydrogeological studies, stochastic-deterministic models could be used, where boundary conditions and infiltration supply are considered stochastic values or functions.

Materials and methods of study. The main differential equations describe the models of the objects of the forecast as a dynamic system with input having processes involving familiar laws of distribution or statistical characteristics. Solving the problem includes determination of characteristics in the output of the studied systems, which are expressed using redistribution of hydrogeological parameters through implementation of theory of stochastic processes or numerical methods, including imitation modeling of boundary conditions and hydrodynamic parameters of groundwater (A. A. Borovkov, 1977, S. M. Yermakov, H. A. Mykhaylov, 1976).

Using such approach allows one to achieve not only engineering-geological and hydrogeological objectives, but also hydraulic, thermodynamic and ecological objectives. Nonetheless, without consideration of thermal factors, it is impossible to arrive at a correct solution. Thus, for metallurgical enterprises, the thermal impact on the geological environment from furnaces and converters equals 2000 – 2200 °C, for machine-building – 400 – 1400 °C, for chemical enterprises the situation is similar. (S. V. Zholudev, 2004, 2008).

Let us consider changes in stress-deformation condition (SDC) of soil structure in case of water filtration in non-isothermal conditions of the territory of an industrial enterprise and estimate its vertical shears.

Field Ω_1 is the zone of water-saturated soil, and field Ω_2 is the zone of aeration, the level of groundwater at the depth l_1 from impermeable horizon (x = 0). Free surface of the level of groundwater (LGW) ($x = l_1$) is considered fixed.

The soil is affected by gravity and in the case of water-saturated soil by Archimedes` principles and filtration force. On the lower surface of the soil at the boundary x = 0, piezometric pressure H_1 and temperature T_1 were given, and on the free surface of LGW ($x = l_1$) the value of piezometric head H_2 was given. The value of temperature T_2 is given on the surface of the soil ($x = l$), and $H_2 > H_1$, $T_2 > T_1$. As a result of difference in pressures and temperatures, heat transfer via filtration flow occurs. The filtration of heat is performed according to the laws of Darcy, Fick and Fourier.

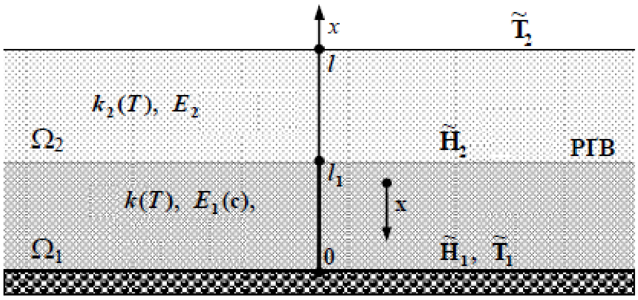

Fig.1. Scheme of soil structure in the conditions of heat transfer during the filtration of groundwater

SDC should be calculated taking into consideration the processes of heat transfer on condition that that there is no shear of lower and upper boundaries of soil or only the lower part of the soil.

The mathematical model of one-dimensional problem of SDC of soil structure in water-saturated and natural conditions has the following expression (I. A. Filatova, 2008, A. P. Vlasyuk, 2000, A. P. Vlasyuk, N. A. Fedorchuk, 2008).

$$\left(\frac{d^2u_i}{dx^2} + \frac{du_i}{dx}\right)\alpha_T\frac{\partial T_i}{\partial x} = X_i,$$

$$X_i = \begin{cases}\gamma_{wc} + \dfrac{dp}{dx}, & i = 1,\\ \gamma_{nc} & i = 2,\end{cases} \quad (1)$$

Where u_i (x) i = 1, 2 – shears in the soil along the *OX* axis in relation to water-saturated (weighed) ($x \in (0; l_1)$ i = 1) and natural (($x \in (l_1; l)$ i = 2) conditions; X_i – mass forces; T_i (x, t), i = 1, 2 – temperature in both layers of soil structure, $x \in (0; l)$; γ_{wc} – specific weight of soil in weighed condition; γ_{nc} – specific weight of soil in natural condition; p – filtration pressure of water, which is defined by

$$p = \gamma_p(h - x) \quad (2)$$

Where h – piezometric head; γ_p – specific weight of fluid; α_T – average coefficient of linear heat distribution in interval of temperatures (T_0, T), which is defined by (M. T. Kuzlo, 2006).

$$\alpha_T = \frac{1}{\overline{T}}\int_0^{\overline{T}}\alpha d\overline{T}, \quad (3)$$

Where $\overline{T}$ = T - T_0, $\alpha = \frac{\Delta l}{l\overline{T}}$ — coefficient of linear expansion; Δl — change in linear sizes of the studied sample.

Boundary conditions for shears are the following

$$L_1 u_1(0) = 0, L_2 u_2(l) = 0, \quad (4)$$

Where L_1, L_2 – differential operators define boundary conditions according to *x* = 0 and *x* = *l*.

Conditions of conjugation on the surface of the level of groundwater for shears

$$u_1(l_1) = u_2(l_1), \quad (5)$$

$$E_1(c)\frac{du_1(l_1)}{dx} - \alpha_T(T_1 - T_0) = E_2\frac{du_2(l_1)}{dx} - \alpha_T(T_2 - T_0), \quad (6)$$

Where $E_1(c)$ – elastic modulus (for soil in water-saturated condition), its dependency on concentration of solutions was obtained in [(M. T. Kuzlo, 2006); E_2 – module of deformation of soil in natural condition.

Solving the problem of change of stress-deformation condition of multi-layer soil structure as a result of filtration flow and change of environmental temperature allows one to define vertical shears of surface of soil structure (Table 1, Fig. 2).

Table 1 Vertical deformation of soil massive

Soil conditions	x	u(x), $*10^{-4}$
weighed condition	0	0
	0,1	-6,64277
	0,2	-1,24801
	0,3	-1,79217
	0,4	-2,03353
	0,5	-2,19563
	0,6	-2,20619
	0,7	-1,97431
natural condition	0,7	-1,97431
	0,8	-2,08038
	0,9	-2,14395
	1	-2,16503

Another important issue is change in properties of groundwater as a fluid affected by thermal processes in the zone of a high-temperature industrial enterprise. The relevance of this research lies in the clear influence of properties of fluid on all seepage, hydrodynamic and migration processes in underground hydrosphere

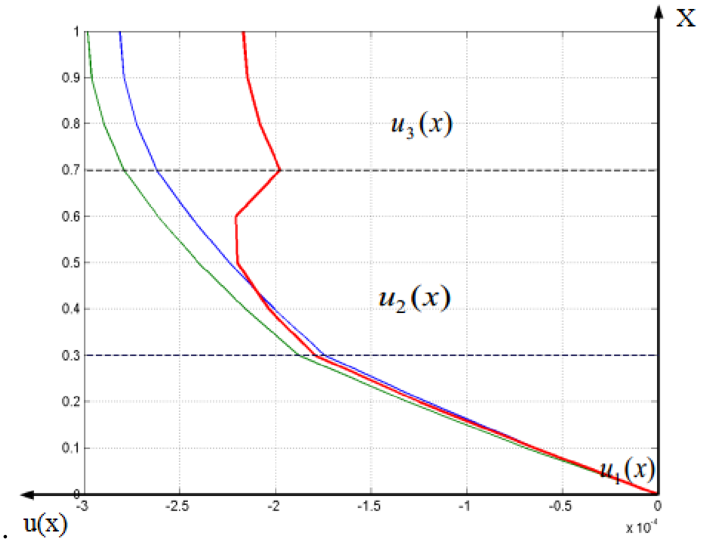

Fig.2. Chart of distribution of vertical shears of soil structure

Dissolved gas and rise in the temperature increase the compressibility of water, though it decreases as the pressure increases.

Density is defined using the following formula

$$\rho = \frac{\gamma}{g}, \qquad (13)$$

Where γ –mass of a unit of volume of water; g – accelaration of free fall.

The density decreases as the temperature increases and increases as the pressure increases. The change in the density of water depends on the change of its temperature, mineralization and compound of dissolved components. For example, viscosity μ of fresh and low-mineralized water at 0 ºC is 1,78·10^{-3} Pa·s, at 10 ºC – 1,31·10^{-3} Pa·s, at 20 ºC – 10^{-3} Pa·s, and at 90 ºC – 0,3·10^{-3} Pa·s.

In a fluid in a quiescent state, pressure connected to its surface, according to Pascal's law, is transmitted with no change to all points of fluid volume (Fig. 3).

If additional external forces are absent, hydrostatic pressure p, which is additional to the atmospheric pressure, inside a fluid in a quiescent state at any point of volume is defined only through mass of above located column of fluid with height h_p which in these conditions equals 0.85 MPa.

$$p = h_p = \rho g h_p, \qquad (14)$$

Because the temperature around the depth changes, the density of water changes also along the depth and the fluid becomes non-homogenous. In this case, hydrostatic pressure in it is defined as follows

$$p = g \int_0^p \rho(z) dz, \qquad (15)$$

Where (z) is a vertical coordinate.

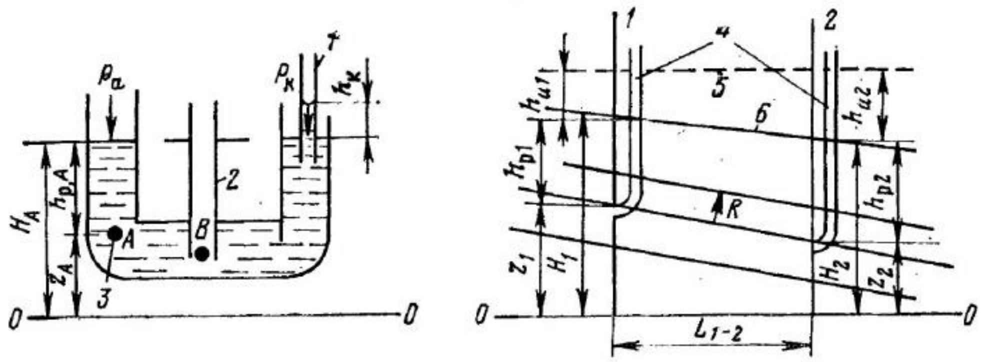

Fig.3. The scheme of hydrostatic pressure and head (a) and hydrodynamic head (b)

1 - Capillary tube; 2 - measuring tube; 3 - elementary unit A; 4 – Pito' tube; 5, 6 – surfaces (5 – hydrodynamic heads of perfect fluid, 6 - hydrostatic heads of moving viscous fluid)

Based on the distribution of the temperature along the depth under a thermal industrial object (S. V. Zholudev, 2004, 2008) and dependency of density of water on the temperature, we can follow the change of water state. At the temperature of 374 ºC, water reaches a critical point and transitions into the state of oxygen and hydrogen gases, at further depth density will increase as the temperature decreases (Fig. 4).

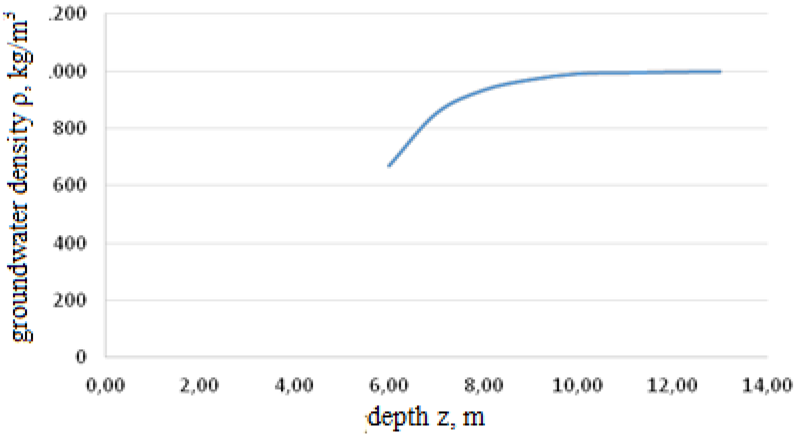

Fig.4. Change in groundwater density by depth under the impact of change in temperature from an industrial object

Change in hydrostatic pressure at variables of density of fluid looks as follows (Fig.5):

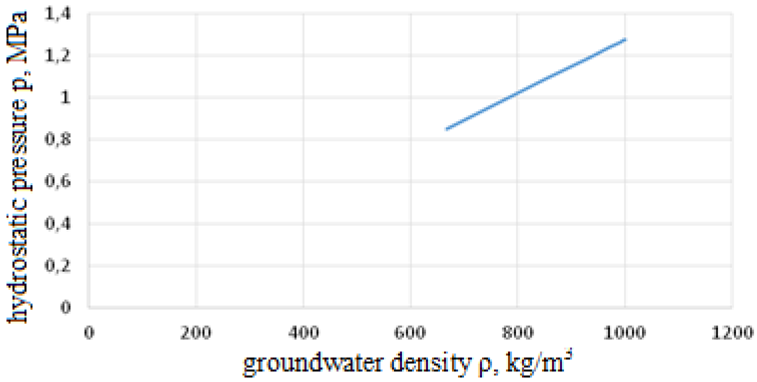

Fig.5. Chart of dependency of hydrostatic pressure on density of water

The net force of hydrostatic pressure pushes out a body placed in water with a force which equals the mass of water in the volume of the body. Water in the capillaries forms concave meniscuses; the difference between pressures lifts the water in a capillary with radius r_K to the height, which equals according to Laplace's formula the point until equilibrium (see Fig. 3, a).

$$h_K = 2\alpha_K / \rho g r_K, \quad (16)$$

The radius of the capillary of the studied water-bearing horizon − r_K = 6.75 m. The analysis of the results of the calculation according to (16) shows increase in the height of the rise of the water in the capillary as its density decreases, i.e. as the temperature of the geological environment increases.

For non-homogenous fluids in conditions where the density of water changes along the depth of water-bearing horizon, i.e. $\gamma = f(z)$, the head becomes a variable and can be introduced as head pressure H_{av}

$$H_{av} = \frac{1}{\gamma_0}\left(p + \int_{z_0}^{2} \gamma dz\right), \quad (17)$$

Where γ_0 is mass of unit of volume of water on the area of comparison z_0 (mass of unit of volume of fresh water may be used); p – layer pressure, measured at the depth z.

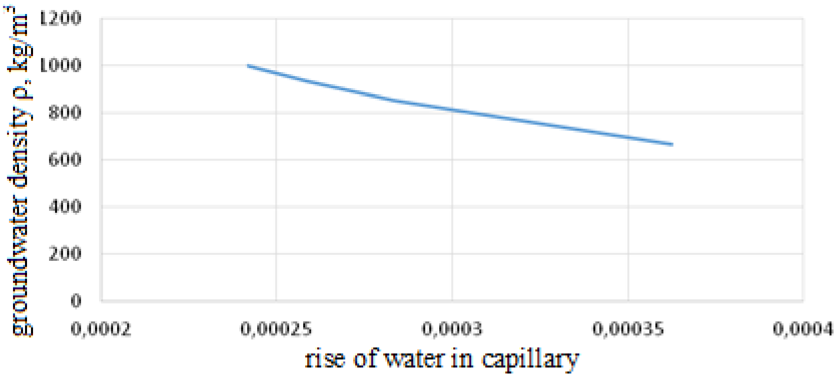

Fig.6. Chart of dependency between height of rise of water in capillary and change of water density

A connection between gradient of head and speed and flow rate of a real fluid can be calculated using the hydraulic values of velocity u and discharge Q_T, which are characterized by striate flow of viscous fluid in a tube of radius R. Velocity u at the distance r from the axis of this tube is described with an equation which shows that velocity in a transversal section of tube changes in accordance with parabolic law (Fig.7) , which in these conditions equals 125.4 cm/hour.

$$u = \frac{\rho g l}{4\mu}(R^2 - r^2), \tag{18}$$

$$u_{max} = \frac{\rho g l R^2}{4\mu}, \tag{19}$$

As a result, the obtained values of velocities of groundwater flow for conditional sandy water-bearing horizon, where values γ and l equal relatively 19.7 $\frac{kN}{m^3}$ and 28 m, and r is 1 − 6 m (fig. 8).

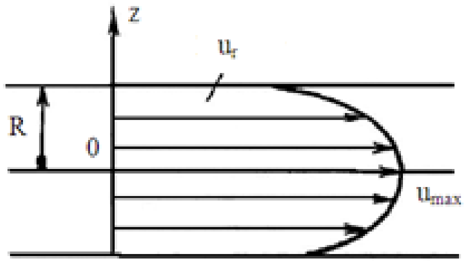

Fig.7. Diagram of velocities u_r according to transversal section of tube at viscous flow of fluid

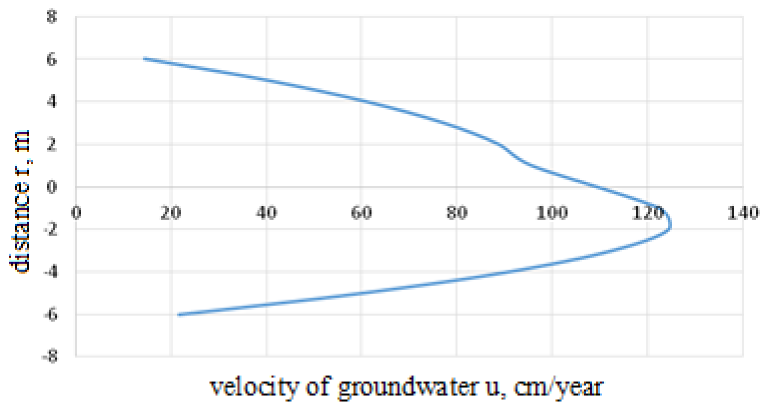

Fig.8. Velocity of groundwater (u) at the distance (r) from the axis of filtration tube of radius R

Flow rate of fluid Q_T in tube is defined as volume of solid of revolution, section of which is given in Fig. 7.

$$Q_T = 2\pi \int_0^R urdr = \frac{\pi \rho g R^4 l}{8\mu}, \tag{20}$$

The radius of tube (water-bearing horizon) R equals 6.5 m, μ = 1.5. In this case, the flow rate of liquid Q_T is 83225,8 m^2/hour.

Let us consider that inside the tube of radius R at the distance r from its axis, there is a flow with section $\omega = \pi r^2$ and length l. The left part of the equation will be expressed using $\gamma \Delta H$, and the right part will be expressed through tangent pressures τ, active on the side surface $2\pi l\mathrm{r}$, i.e. $2\pi l\mathrm{r}\tau$. As a result

$$\gamma\Delta\mathrm{H} = \frac{2\pi l\mathrm{r}\tau}{\pi\mathrm{r}^{2}l} = \frac{2l\tau}{\mathrm{r}} \text{ або } \tau = 0{,}5\gamma\mathrm{r}l \ , \quad (21)$$

This dependency is known as the Hagen–Poiseuille equation. Average velocity u_{av} is found as a ratio of Q_T to the area of section of tube πR^2

$$u_{av} = \frac{\rho g R^2 l}{8\mu}, \quad (22)$$

According to the formula (22), the average velocity is proportional to the square of radius of the tube. It equals 62.7 cm/hour.

In thin capillaries, water, apart from viscosity, has additional structural density as a result of molecular impact of solid surface. Water is a viscoelastic body with initial shear stress τ_0. In this case, it is considered that structural (molecular) bonds at a crossing of rocks are distributed uniformly. For such conditions, the tangent stress according to the law of viscoelastic flow (Bingham-Shvedov law) can be expressed as follows (Fig.9)

$$\tau = \tau_0 + \mu\left|\frac{du}{dn}\right| , \quad (23)$$

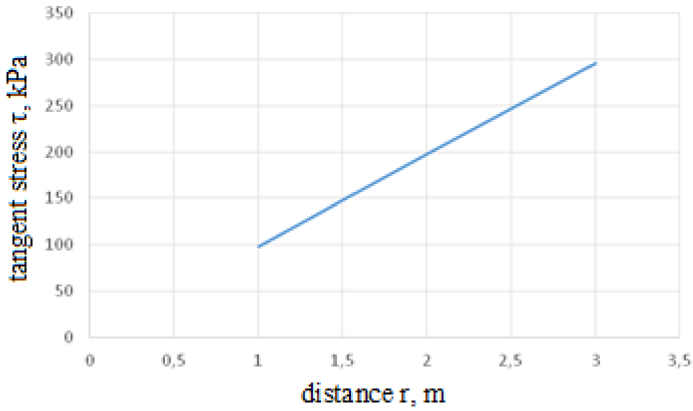

Fig.9. Chart of relation of values of tangent stress to the distance from axis of tube

As we see from (23), at $\tau < \tau_0$ the flow is absent: fluid can move only at the condition $\tau > \tau_0$. The changes of tangent stress τ correspond to changes of the physic-mechanical properties of the underlying rocks. If the difference between heads $H_1 - H_2$ is added to the ends of capillary of radius *R*, the net force of hydrostatic pressure equals $P = \rho g(H_1 - H_2)\pi R^2$. Initial gradient of flow I_0, which corresponds to the moment of start of water flow, can be found as follows

$$I_0 = \frac{H_1 - H_2}{l} = \frac{2\tau_0}{\rho g R} = \frac{2\tau_0}{\gamma R}. \quad (24)$$

The value of I_0 for these conditions obtained through the calculations equals 1.5 m.

Conclusions. Analysis of the existing methods and calculation of several significant physical, hydraulic and hydrodynamic parameters of a hydrogeological environment which was made using these methods, showed that:
- At constant temperature, the change in pressure causes change of initial volume of water according to Hooke`s law;
- Presence of dissolved gas and rise in the temperature increase the water density;
- The density decreases as the temperature rises and increases as the pressure rises;
- Change of water viscosity depends on the change of its temperature, mineralization and compound of dissolved components.

We calculated:
- The values of vertical shears of soil structure;
- The change in the density of groundwater in relation to temperature;
- Hydrostatic pressure p inside fluid in a quiescent state at any point of volume;
- Hydrostatic pressure in case of change in temperature of rocks along the depth and viscosity of water at condition of non-homogenous fluid;
- The height of water rise in the capillary according to Laplace`s formula;
- The velocity of flow of groundwater u at the distance r from the tube axis;
-average velocity u_{cp} and flow rate Q_T in the tube according to the Hagen–Poiseuille equation;
- Initial gradient of groundwater flow I_0.

Thus, the results of the calculations show the clear influence on hydrogeological conditions of changes in thermal regime of groundwater of territories adjacent to high-temperature industrial enterprises and prove the necessity of taking into consideration thermal processes during hydrogeological and engineering-geological research.

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