Hydrogeological and Geothermal Parameters of Rocks by Temperature Measurements

Khodyreva E. Ya., Stanin A.V., Gavrilov A.G.

Kazan State University, Kazan, Russia.

E-mail: Ella.Khodyreva@ksu.ru

Keywords: Temperature measurements, heat flow, geothermal gradient, hydrodynamic parameters.

ABSTRACT

The basic source of information about power condition of bowels of the Earth is the heat flow. Its calculation in accordance with Fourier law is possible only if there is exact data about geothermic gradients and heat conductivity of rocks. It is necessary for geothermic gradients calculation to measure experimentally the temperature in deep boreholes with setting heat regime. Geothermal investigation, that we carried out in more than 400 long-standing deep boreholes located in Russia, Ukraine, Belarus and other regions have shown that in most cases the heat flow in upper lays of sedimentary thickness is not constant, and geothermograms have non-linear character. In connection with that the depth of investigated objects is of particular importance. The analysis of results of geothermic investigation has shown that the depth heat flow may be distorted owing to the influence of structural, tectonic, geomorphologic and hydrogeological factors. In active water-exchange zones and especially in areas of alimentation and discharge of underground waters the prevailing influence on thermal field is rendered by the convective heat flow component, effecting the total heat flow value and form of geothermograms. It is developed the method of separation of conductive and convective heat flow components, were defined velocities of fluid motion and is given the quantitative estimation of hydrogeological parameters by temperature measurements. Heat conductivity and thermal capacity parameters are directly connected to the structural performances of rocks, in particular by porosity. Investigation of rocks, identical on an elemental composition, but with a different porosity, has allowed to place quantitative connection between porosity and thermal capacity in a temperature range from 0 °C to 300 °C.

1. INTRODUCTION

The formation of thermal fields takes place on three levels – global, regional and local. Global thermal fields are associated with processes in the mantle of the Earth, regional fields are due to the stationary radiogenic component of the crust heat flow in general and local fields are due to the deformation of rocks, sedimentation, migration of fluids and other processes taking place in upper layers of the sedimentary thickness. The basic source of information about power condition of bowels of the Earth is the heat flow. Its calculation in accordance with Fourier law is possible only if there is exact data about geothermic gradients and heat conductivity of rocks. The heat conductivity of rocks may be determined with error 5-10% as in laboratory as in-situ conditions. It is necessary for geothermic gradients calculation to measure experimentally the temperature in deep boreholes with setting heat regime. Geothermal investigation, that we carried out in more than 400 long-standing deep boreholes located in Russia, Ukraine, Belarus and other regions have shown that in most cases the heat flow in upper lays of sedimentary thickness is not constant, and geothermograms have non-linear character (Khodyreva, 1997). In connection with that the depth of investigated objects is of particular importance. Thermistor and varicond thermometers with error no more than 0.01-0.05^{0}C measured the temperatures with details from 0.5 to 5 m, the mean depth of measuring are 2000-3000 m. Several boreholes within limits of each investigated region were chosen as standard, in it were carried out repeated temperature measuring at intervals from several days to several years.

The analysis of results of geothermic investigation has shown that the depth heat flow may be distorted owing to the influence of structural, tectonic, geomorphologic and hydrogeological factors. In active water-exchange zones and especially in areas of alimentation and discharge of underground waters the prevailing influence on thermal field is rendered by the convective heat flow component, effecting the total heat flow value and form of geothermograms. On example of Pripyat depression (Belarus) is developed the method of separation of conductive and convective heat flow components, were defined velocities of fluid motion and is given the quantitative estimation of hydrogeological parameters by temperature measurements. The evaluation of the heat flow is impossible without the information on thermal properties of rocks – for heat conductivity and thermal capacity. These parameters are directly connected to the structural performances of rocks, in particular by porosity. Investigation of rocks, identical on an elemental composition, but with a different porosity, has allowed to place quantitative connection between porosity and thermal capacity in a temperature range from 0 to 300^{0}C.

2. OBJECT OF INVESTIGATION. BRIEF GEOLOGICAL CHARACTERISTICS.

The results of the study are based on the experimental geothermal investigations, carried out in more than 400 long-standing deep boreholes with the depth of 500 to 3500 m, and located within the limits of Dnieper-Donets and Pripyat depressions, Voronezh anticline, central part of Ukrainian crystalline shield, Carpathian and other regions. The choice of these structures as the objects of investigation is conditioned by the fact, that each of them, owing to the peculiarities of geological features can serve the model system fox detailed investigation of the one of the main factors of thermal fields formation.

The Dnieper-Donets depression (DDD) refers to graben-like extension structures, which are characterized by the elevated values of the heat flow, increased thickness of sedimentary layer and reduced thickness of the crust in a whole. The Upper-Rheinian graben and other structures of the similar type can serve the analogy of the Dnieper-Donets rift (Meier et. al., 1982). Geological sequence of DDD is represented by thickness of sedimentary deposits from 3-4 km to I7 km. The intensive water-exchange zone is spreading up to the depth of 300-500 m in general, and still deeper conduction predominantly performs heat transfer.

The Pripyat depression as well as the DDD is the main compound of the common Pripyat-Dnieper-Donets Paleozoic avlacogen. The sedimentary layer thickness is 4-6 km; the zone of hydrogeological factor influence reaches 2500 m.

The Ukrainian crystalline shield (UCS) referring to the areas of ancient consolidation, occupies the central position with-in the limits of southwestern margin of the East-European platform. The earth crust thickness is an average 46-48 km that coincides with the analogues value for Voronezh anticlise and indicates the identity of origination of the mentioned structures and their relationship with a single ancient Sarmatian shield.

The Carpathian region, referring to the areas of Alpine folding represents the zone of increased tectonic and geothermal activity, there it is assumed the availability of abyssal heat source (Kutas, 1978), that allows to carry on comparative analysis of stationary and unstationary thermal fields of geological structures.

3. MANTLE AND CRUST COMPONENTS OF THE HEAT FLOW

The quantitative estimation of mantle q_m and crust q_c components of the heat flow is made in comparing of the thermal fields DDD and Grivorozhsk-Cremenchuk zone of UCS. The notion of energetic state of entrails of the examined regions gives the empirical dependence diagrams of average, minimum and maximum values of temperature from the depth, indicated on fig.1. The comparison of functional dependences $T_{av} = f\ (H)$, $T_{min} = f_1\ (H)$ and $T_{max} = f_2\ (H)$ makes it possible to conclude, that the central part of the UCS is characterized by lesser geothermal activity in comparison to DDD. The UCS differs from DDD not only by lesser absolute magnitude of temperature average values, but also by lesser temperature range on the similar depth $\Delta T = T_{max} - T_{min}$ as the result of which there reduced the probability of horizontal heat-mass transfer origination and fluid motion under the influence of horizontal temperature gradient (Khodyreva, 1983). Such a difference in geothermal regime of two neighboring geological structures may be related with the various values of heat flow crust component, as mantle components q_m according to data (Smyslov et. al., 1979) for DDD and Crivoy Rog are the same and equal to 12,4 mW/m^2. The analogous value q_m = 11-18 mW/m^2 for UCS is given in (Kutas, 1982), and it is noted, that the contribution of the mantle component for the whole East-European platform changes negligibly. The average value of a heat flow in the region of Crivoy Rog, calculated according to schists, quartz-carbonate rock and marbles K_3^2 is q = 27,5 mW/m^2. So, the crust component of the heat flow, that has apparently radiogenic character as on all of the ancient shields, makes q_c = 15,1 mW/m^2.

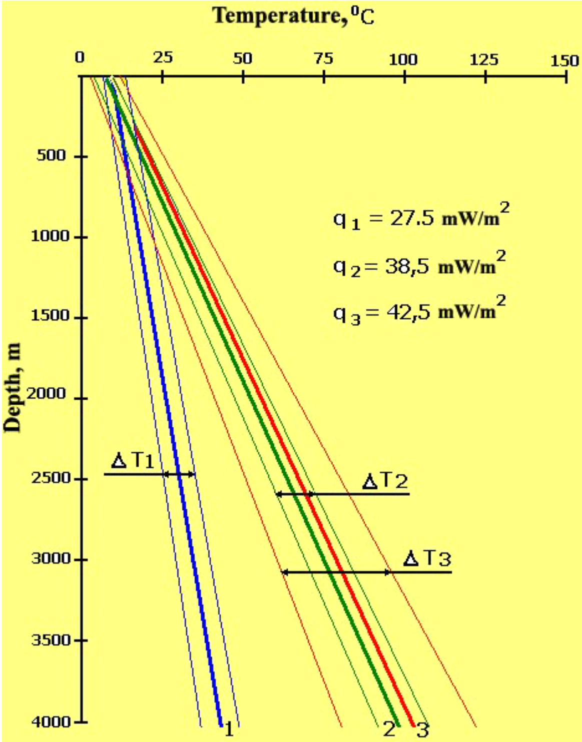

Fig.1.Experimental graphs of depth dependence of average, minimal and maximal temperatures for Crivoy Rog (I), Pripyat (2) and Dnieper-Donets Depression (3)

For sedimentary basins of oil-gas accumulation areas in addition to the mantle and stationary radiogenic components there exists also the dynamic component of a crusty heat flow q_d, caused by the deformation of rooks, sedimentation, hydrogeological and other factors of the local nature. For the DDD, where the lowest limit of heat flow, identified according to the geothermal bench mark method (Khodyreva, 1981), represents 42.5 mW/m^2 the share of the dynamic component of crust heat flow is q_d = 15 mW/m^2, i.e. for the sedimentary basins areas of oil-gas accumulation value of the dynamic component q_d is comparable to stationary radiogenic q_s and mantle q_m components. It is to be noted, that the availability of q_d is responsible for the absence of the linear dependence between the radiogenic generation of neat and the observable heat flow, especially in the tectonically active areas where q_d may excess the radiogenic component q. The ratio of the type $q = q_0 + CA$, where A - heat generation value, mast be fulfilled for tectonically stable structures, for example shields, where crust heat flow as it was mentioned above, is, in general, radiogenic. The analogous character of heat flow dependence upon heat generation is indicated in (Smirnov, 1980), where function $q= f\ (H)$ linearity is established only for homogeneous structures of the Ukrainian and Baltic shields.

4. THE RELATIONSHIP OF GEOTHERMAL PARAMETERS WITH TECTONIC REGIME.

It is known, that different distribution of temperatures and thermal fields corresponds to various tectonic regimes (Khodyreva, 2000). Tectonic activization of previously stable area takes place under the influence of thermal impulse, originating in great depths. One-to-one correspondence exists between thermal regime and completion time of the last tectonic-magnetic event. The relationship of the thermal field with tectonic regime allows making quantitatively evaluation of geological structures stability according to geothermal parameters. We introduced the notion of instability coefficient $\chi = (T_{max} - T_{min})/T_{av}$, where T_{av}, T_{min} and T_{max} are determined by experimental graphs, represented on fig.1. Minimal values χ characterize the most ancient structures – shields. Within more young structures possessing the elevated geothermal activity the temperature range ΔT increases, geothermal field is characterized by maximal heterogeneity and the instability coefficient increases. Comparison of the examined structures according to average χ values (0,22 - Criroy Rog; 0,24 - Voronezh anticlise; 0,50 - DDD; 0,66 - Pripyat depression; 0,78 - Carpathian region) makes it possible to draw qualitative and quantitative conclusion about the increase of instability coefficient from ancient consolidation areas to young structures with the elevated geothermal activity. Moreover, not only absolute χ values differ, but also the character of χ variation with the depth. Comparative analysis of dependences $\chi = f(H)$ (fig.2) allows to make the following conclusions:

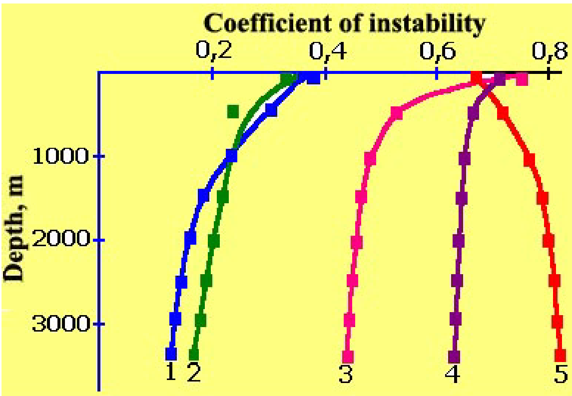

Fig.2.Coefficient of instability as a function of the depth for Krivoy Rog (I), Voronezh anticlise (2), Dnieper-Donets (3) and Pripyat (4) Depressions, Carpathian region (5)

1. The central part of UCS and Voronezh crystalline massif are characterized by minimal χ values and the same character of dependence $\chi = f(H)$, which agrees with the similar origination of the mentioned structures and their belonging to the single ancient Sarmathian shield.

2. The increase of χ with the depth is noted for Carpathian region, where it is assumed availability of the abyssal thermal source, i.e. on approaching the source the thermal instability of the structure increases that is typical for the regions with unstationary thermal regime.

3. The DDD and Pripyat depression according to average χ values occupy the intermediate position between the ancient shields and young geothermal active structures. For the sedimentary basins of oil-gas accumulation areas is possible the constancy as well as the variation of instability coefficient with the depth. The function $\chi = f(H)$ view depends on relationship of conductive and convective components of heat flow ill the upper layers of sedimentary thickness.

5. CONDUCTIVE AND CONVECTIVE COMPONENTS OF HEAT FLOW. HYDROGEOLOGICAL PARAMETERS.

In the influence zone of the hydrogeological factor the prevailing effect on thermal field is rendered by the convective component of heat flow, effecting the total q value and form of geotermograms.

The availability of q_{cv} leads to the functional dependence of total heat flow upon depth $q = q_{cd} + q_{cv} = f(H)$, as $q_{cv} = \pm v c\rho \cdot (T_2 - T_1) = \pm v c\rho \cdot G_{obs} \cdot \Delta H$ depends upon the depth interval ΔH, where the motion of a fluid takes place.

As the model system for quantitative evaluation of the convective component of heat flow and establishment of relationship between hydrogeological and geothermal parameters the Pripyat depression is chosen, where in the geological section of sedimentary layer are definitely recognized two hydrothermal complexes, differing in pressure of underground water and rate of water-exchange. The upper above-salt complex D_3dn is characterized by active water-exchange, here $q = q_{cd} + q_{cv}$; the lower - by slowed, practically immobile, here heat transfer is made by conduction $q = q_{cd}$ and $q_{cv} = 0$, as the saliferous stratum D_3lb in a view of hydrogeology may be considered as the ideal water resisting barrier. The comparison of a really observed geothermal gradient of above-salt complex $G_{obs}D_3dn = f(q_{cd}, q_{cv})$ with that value $G_{cd}D_3dn$, which would have existed in conditions of conductive heat transfer, shows that $G_{obs}D_3dn$ depending on direction of fluid motion (sing ± at a rate v) $G_{obs}D_3dn$ may be larger as well as less than $G_{cd}D_3dn$.

Butt in any case on the borderline of two complexes there will be temperature anomaly ΔT conditioned by the availability of q_{cv}, which may be used as the correction on the influence of a hydrogeological factor $\Delta T = \Delta H \cdot (G_{cd}D_3dn - G_{obs}D_3dn)$. Quantitative relationship of hydro-geological characteristics with geothermal parameters is realized with the help of a ratio $\pm v = (\lambda_{cd}D_3dn/c\rho \cdot \Delta H) \cdot \{(G_{cd}D_3dn/G_{obs}D_3dn) - 1\}$. Thus, to calculate the motion rate of a fluid v, the convective component of a heat flow q_{cv} and temperature correction ΔH, it is necessary to restore that geothermal gradient value of above-salt complex $G_{cd}D_3dn$, which would have existed in conditions of conductive heat transfer (Khodyreva, 1987).

The results of calculation for 15 the drill-holes under investigation of the Pripyat depression are presented in the table1. The comparison of conductive and convective components of the heat flow shows, that q_{cv} may reach 30% from q_{cd}, therefore in calculating q according to Fourier law in the influence zone of a hydrogeological factor the error in determination of a real value of a heat flow is 30%. (Khodyreva, 1998). As in several drill holes of the Pripyat depression the Devonian above-salt thickness D_3dn is spread up to the depth of more than 2000 m, the considered question is of a particular interest in view of the choice of optimal depth in determining the true q value and introduction of corrections on q_{cv} in geothermal researches in drill holes of a small depth. So as the really observed geothermal gradient of above-salt thickness is the function of the conductive as well as the convective components of the heat flow, there arises a problem: according to the measured value $G_{obs}D_3dn$ to restore q_{cd} and q_{cv} for those drill-holes, where the geothermal studies concern only the upper hydrodynamic store and there is no possibility to determine the true value of the depth heat flow.

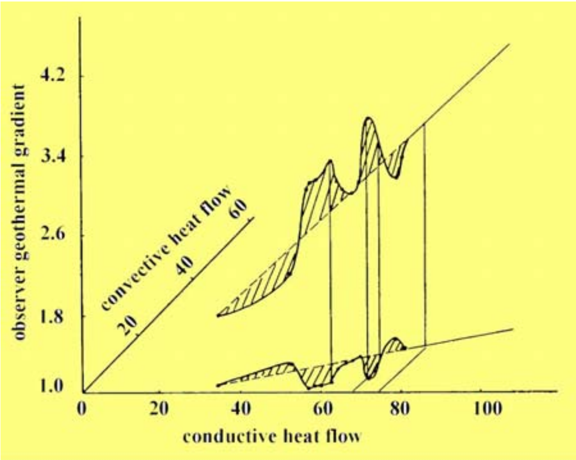

Fig.3.Pripyat depression. Geothermal gradient of above-salt sediments as a function of conductive and convective heat flow components.

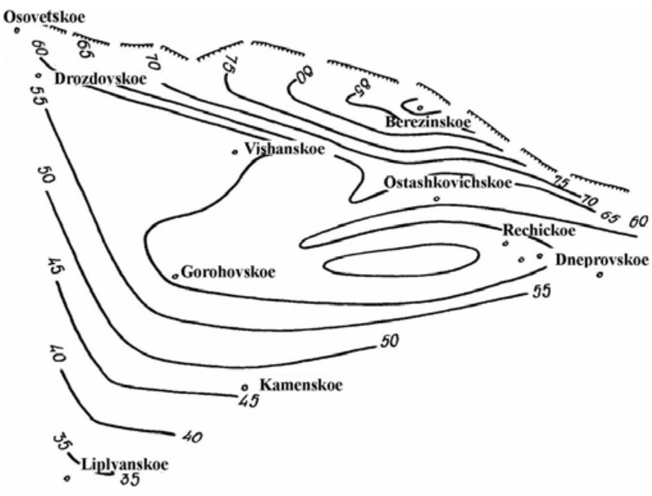

Fig.4. Pripyat depression. Scheme of distribution of conductive heat flow.

For this purpose there was drawn three-dimensional diagram of dependence $G_{obs}D_3dn = f\ (q_{cd}, q_{cv})$, with the help of which according to the known value $G_{obs}D_3dn$ it is possible to find the corresponding values q_{cd} and q_{cv} (fig.3). It must be noted, that in the sphere of function $G_{obs}D_3dn = f\ (q_{cd}, q_{cv})$ determination there are ambiguity zones, where function monotony is broken. Uncertainty may be removed, when taking into account the spatial position of the examined drill-hole on the considered territory. For example, the average value $G_{obs}D_3dn$ = 3,24^{O}C/100m, determined on the drill-hole Dneprovsksya-4, may be placed in accordance with four pairs of (q_{cd}, q_{cv}) values, but as the most probable there was chosen the pair (60,5; 2,5 mW/m^2), that does not contradict general regularities of q_{cd} and q_{cv} distribution, represented on fig.4 and fig.5.

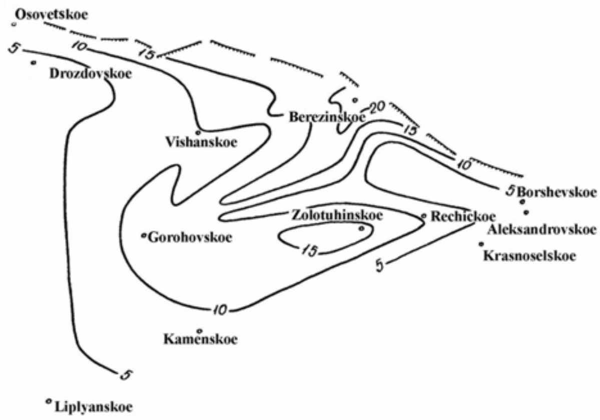

Fig.5. Pripyat depression. Scheme of distribution of convective heat flow.

For the comparison of the hydrogeological characteristics of the regions under investigation we introduced the notion of the specific convective heat flow $\tilde{q}_{cv} = q_{cv}/\Delta H$, being an invariant concerning the interval of the fluid motion ΔH and allowing one to take into account the contribution of the unit of volume of the two phase system "solid-liquid" to the convective component of the heat flow.

The specific convective heat flow, scale of which [W/m^3], by if a physical sense may serve as a convective analogue of the value of heat generation.

On the fig.6 presented scheme of distribution of the fluid motion rate for the Pripyat depression. The rate of the fluid motion for the areas under investigation varied for 0,04 cm/year to 1,96 cm/year.

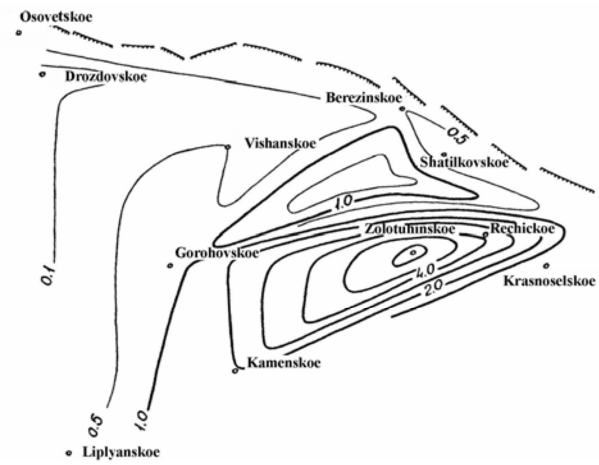

Fig.6. Pripyat depression. Scheme of distribution of the fluid motion rate.

In the applied aspect the information about conductive and convective components of the heat flow may be used for the evaluation of oil-gas-bearing perspectives of abyssal structures according to geothermal data. The relation of q_{cd} and q_{cv} influences the migration of hydrocarbons in heterogeneous geothermal field, and if the distant lateral migration is most probable under the influence of horizontal temperature gradient, conditioned by difference in conductive components of the heat flow of oil-gas-formation zones and areas of oil-gas-accumulation, then vertical migration apparently relates to convective component q_{cv}, in general.

6. CONCLUSIONS

We carried out experimental temperature measurements in more than 400 long-standing deep boreholes, located in Russia, Ukraine and other regions. The deeps of measuring were of 500 to 3500 m, details from 0.5 to 5 m, error no more than 0.01-0.05˚C. For sedimentary basins of oil-gas accumulation areas were calculated mantle, stationary radiogenic and dynamic components of a crusty heat flow. We introduced the notions of instability coefficient χ of geological structures and determined χ by temperature measurements. On example of Pripyat depression (Belarus) is developed the method of separation of q_{cd} and q_{cv}, were defined velocities of fluid motion and is given the quantitative estimation of hydrogeological parameters by temperature measurements.

REFERENCES

Khodyreva E.Ya. On influence of basic factors of thermal field formation on the form of geothermograms. *Proceedings International conference The Earth's thermal field and related research methods.* Moscow. 1997. 44 - 48.

Khodyreva E.Ya. Variations of geothermal parameters within local and regional geological structures. *J. Georesources.* # 2 [2]. 2000. 45 – 46.

Meier R., Hurtig E., Ludwig A. Explosive tectonic and European thermal field. *Thermal field of Europe.* Moscow. 1982. 134-142.

Kutas R.I. *Heat flows field ant thermal model of the Earth's crust*. Kiev. 1978. 148.

Kutas R.I. Geothermal model of the Earth's crust of Ukrainian shield. *Thermal field of Europe*. Moscow. 1982. 294-302.

Smyslov A.A. Moiceenko U.I., Chadovich T.Z. *Thermal regime and the Earth's radioactivity*. Leningrad. 1979. 191.

Khodyreva E.Ya. Method of benchmark horizon. *Theses of All-Union Scientific-Technical Conference Problems of mountain thermophysics.* Leningrad. 1981. 56-57.

Khodyreva E.Ya. Initial geothermal fields of oil-gas accumulation areas. *Theses All-Union Conference Geothermal investigation in Central Asia and Kazakhstan.* Ashkhabad. 1983. 132-133.

Smirnov Ja.B. *Thermal field of the territory of the USSR (explanatory note to the maps of the heat flow and abyssal temperatures, sc. I: I0000000).* Moscow. 1980. 150.

Khodyreva E.Ya. Conductive and convective heat flow of the Pripyat basins areas of oil-gas formation. *J. Petroleum Industry. Oil-gas geology and geophysics.* #7. 1987. 14 – 17.

Khodyreva E.Ya., Kushtanova G.G. Vertical and lateral variations of geothermal parameters within local geological structures. *Proceedings International conference The Earth's thermal field and related research methods*. Moscow. 1998. 119-122

Table 1. Pripyat depression. Hydrodynamic parameters.

Structure, number of well	$G_{obs}D_3dn$ [°C/100m]	$G_{cd}D_3dn$ [°C/100m]	*1.1.1.1.1* [cm/year]	q_{cd} [mW/m^2]	q_{cv} [mW/m^2]
Beresinsk - 1	3,92	5,15	0,64	92,2	21,2
Shatilkovsk - 4	3,68	3,86	0,12	69,1	3,3
Ostashkovich - 18	2,94	3,28	0,18	58,8	6,4
Borchovsk - 13	3,26	3,38	0,05	60,5	2,3
Sosnovsk - 40	2,61	3,67	1,88	65,7	19,0
Marmovichsk - 2	3,08	3,34	0,22	59,9	4,7
Vishansv - 18	2,76	3,28	0,48	58,8	9,25
Krasnoselsk - 213	3,08	3,19	0,04	57,0	2,0
Drosdovsk - 1	3,08	3,12	0,04	55,9	0,74
Osovetsk - 1	2,70	3,34	0,81	59,9	11,2
Zolotuchinsk - 1	2,90	3,80	6,44	68,0	16,6
Gorochovsk - 2	2,77	3,41	0,82	61,0	11,8
Kamensk - 1	1,92	2,54	1,96	45,5	9,2
Aleksandrovsk - 8	3,00	3,09	0,04	55,3	1,6
Lipljansk - 1	1,73	1,83	0,21	32,8	1,9