Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Quantitative Estimation of Hydrogeological and Geothermal Parameters by Experimental Data

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Keywords: Temperature measurements, conductive and convective heat flow, hydrological parameters, porosity, thermal properties of rocks.

ABSTRACT

Statistical analyses of the results of the temperature measurements 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 the upper layers of sedimentary material is not constant. In active water-exchange zones and especially in areas of alimentation and discharge of underground waters, the prevailing influence on the thermal field is the convective heat flow component. For one example, the Pripyat depression (Belarus), the method of separation of conductive and convective heat flow components is developed, where the velocities of fluid motion are defined and the quantitative estimation of hydrological parameters is given by temperature measurements. For the comparison of the hydrological characteristics of investigated regions we introduce the concept of the specific convective heat flow, which is invariant about the fluid motion interval. The evaluation of heat flow is impossible without information on the thermal properties of rocks, specifically for heat conductivity and thermal capacity. These parameters are directly connected to the structural performance of rocks, in particular by porosity. Investigation of rocks, identical in elemental composition but with different porosities, has allowed us to make a quantitative connection between porosity and thermal capacity in a temperature range from 25 to 300^{o}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 the upper layers of the sedimentary thickness. The basic source of information about power conditions in the interior of the Earth is the heat flow. Its calculation in accordance with Fourier's law is possible only if there is exact data about geothermal gradients and the heat conductivity of rocks. The heat conductivity of rocks in in-situ conditions may be determined in the laboratory with 5-10% error. It is necessary for geothermal gradient calculations to measure experimentally the temperature in deep boreholes with a static heat regime. The geothermal investigations 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 the upper layers of sedimentary thickness is not constant and geothermograms (dependence diagrams of temperature from the depth) have a non-linear character (Khodyreva, 1997). The depth of investigated objects is of particular importance. The depth distant thermometer had error no more than 0.01-0.05 ^{0}C and we measured the temperature at intervals from 0.5 to 5 m. The mean depth of measuring was 2000-3000 m. Several boreholes within the limits of each investigative region were chosen as standards, and repeated temperature measurements were carried out in these boreholes at intervals from several days to several years. The analysis of results from geothermic investigation has shown that the at depth heat flow may be distorted due to the influence of structural, tectonic, geomorphologic and hydro-geological factors. In active water-exchange zones and especially in areas of alimentation and discharge of underground waters, the prevailing influence on the thermal field is the convective heat flow component, which affects the total heat flow value and the form of geothermograms. For one example, the Pripyat depression (Belarus), the method of separation of conductive and convective heat flow components is developed, where the velocities of fluid motion are defined and a quantitative estimation of hydro-geological parameters is given by temperature measurements. The evaluation of heat flow is impossible without information on the thermal properties of rocks, specifically heat conductivity and thermal capacity. These parameters are directly related to the structural performances of rocks, in particular by porosity. Investigation of rocks that are identical in elemental composition but have different porosities has allowed us to make a quantitative connection between porosity and thermal capacity in the temperature range from 25 to 300 ^{o}C.

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

In the influence zone of the hydro-geological factor, the convective component of heat flow is the dominant control on the thermal field, affecting the total $\boldsymbol{q}$ value and the form of geothermograms. A geothermogram is a diagram of the temperature dependence on depth. The availability of $\boldsymbol{q_{cv}}$ leads to the functional dependence of total heat flow upon depth

$$q = q_{cd} + q_{cv} = h(H)$$

as $$q_{cv} = vcp(T_2 - T_1) = \pm vcp \cdot G_{obs} \cdot \Delta H$$

(*depends upon the depth interval* $\boldsymbol{\Delta H}$*, where the motion of a fluid takes place.*)

where $\boldsymbol{v}$, $\boldsymbol{c}$, $\boldsymbol{\rho}$ are the motion rate, thermal capacity and density of a fluid.

The Pripyat depression is chosen as a model system for quantitative evaluation of the convective component of heat flow and establishment of a relationship between hydrogeological and geothermal parameters. The Pripyat

depression and the Dnieper-Donets depression (DDD) are the main parts of the common Pripyat-Dnieper-Donets Paleozoic avlacogen. DDD refers to graben-like extension structures, which are characterized by the elevated values of the heat flow, increased thickness of the sedimentary layer and reduced thickness of the crust in a whole. The Upper-Rhein graben and other structures of the similar type can serve as analogies to the Dnieper-Donets rift *(Meier et. al., 1982)*. The geological sequence of the DDD is represented by sedimentary deposits that are 3 - 4 km to I7 km thick. In general, the intensive water exchange zone is above 300-500 m depths and, below this depth, conduction dominates heat transfer. The thickness of the sedimentary layer in the Pripyat depression is 4-6 km, and the zone of hydrogeological factor influence reaches to 2500 m.

Two hydrothermal complexes are definitely recognized in the sedimentary layer of the Pripyat depression's geological section. They differ in the pressure of underground water and the rate of water-exchange.

- The upper above-salt complex D_3dn is characterized by active water-exchange, and $q = q_{cd} + q_{cv}$.
- The lower complex is characterized by slowed, practically immobile, water-exchange, and here heat transfer is made by conduction $q = q_{cd}$ and $q_{cv} = 0$, as the saliferous stratum D_3lb may be considered as the ideal water resisting barrier from a hydrogeology perspective.

The comparison of an observed geothermal gradient from the above - salt complex $G_{obs}D_3dn = f(q_{cd}, q_{cv})$ with the gradient $G_{cd}D_3dn$ that would have existed in conditions of conductive heat transfer, shows that $G_{obs}D_3dn$ may be larger or less than $G_{cd}D_3dn$ depending on the direction of fluid motion (sing ± at a rate v) $G_{obs}D_3dn$. But in any case, on the boundary of two complexes there will be a temperature anomaly ΔT, conditioned by the availability of q_{cv}, which may be used as the correction on the influence of a hydro-geological factor

$$\Delta T = \Delta H \cdot \left(G_{cd} D_3 dn - G_{obs} D_3 dn\right)$$

A quantitative relationship between hydro-geological characteristics and geothermal parameters is realized with the help of a ratio:

$$\pm v = \left(\frac{\lambda_{cd} D_3 dn}{c\rho \cdot \Delta H}\right) \cdot \left(\left(\frac{G_{cd} D_3 dn}{G_{obs} D_3 dn}\right) - 1\right)$$

Thus, to calculate the rate of motion of a fluid v, the convective component of heat flow q_{cv} and the temperature correction ΔH, it is necessary to use the geothermal gradient value from above-salt complex $G_{cd}D_3dn$ that would have existed in conditions of conductive heat transfer (Khodyreva, 1987).

The results of the calculation for 15 the boreholes under investigation in the Pripyat depression are presented in the Table 1. The comparison of conductive and convective components of the heat flow shows that q_{cv} may reach 30% of q_{cd}; therefore calculating q according to Fourier's law in the influence zone of hydro-geological processes may result in 30% error relative to the a real heat flow value (Khodyreva, 1998). In several boreholes of the Pripyat depression, the Devonian above-salt thickness D_3dn extends up to a depth of more than 2000 m. Consequently, our present discussion is of a particular importance to the choice of the optimal depth at which to determine the true q value and the use of corrections on q_{cv} in geothermal studies in shallow boreholes. So, because the observed geothermal gradient of the above-salt thickness is a function of the conductive and the convective components of the heat flow, there arises a problem: according to the measured $G_{obs}D_3dn$ value, to restore q_{cd} and q_{cv} for those boreholes, 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. For this purpose, a three-dimensional diagram of dependence $G_{obs}D_3dn = f(q_{cd}, q_{cv})$ was drawn, and, with the help of this diagram, it is possible to find the values of q_{cd} and q_{cv} that correspond a known value $G_{obs}D_3dn$ value (fig.1). 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's uniqueness is broken. Uncertainty may be removed by taking into account the examined borehole's spatial position in the considered territory. For example, the average value $G_{obs}D_3dn$ = 3.24^{O}C/100m determined for borehole Dneprovsksya-4 borehole may be placed in accordance with four pairs of (q_{cd}, q_{cv}) values and the probable values can be chosen there (60.5; 2.5 mW/m^2) that do not contradict general regularities of the q_{cd} and q_{cv} distribution. This is represented in fig.2 and fig.3.

Table 1: Pripyat depression. Hydrodynamic parameters

Structure, number of well	$G_{obs}D_3dn$ [^{o}C/100m]	$G_{cd}D_3dn$ [^{o}C/100m]	V [cm/year]	q_{cd} [mW/m^2]	q_{cv} [mW/m^2]
Beresinskaya - 1	3,92	5,15	0,64	92,2	21,2
Shatilkovskaya - 4	3,68	3,86	0,12	69,1	3,3
Ostashkovichskaya - 18	2,94	3,28	0,18	58,8	6,4
Borchovskaya - 13	3,26	3,38	0,05	60,5	2,3
Sosnovskaya - 40	2,61	3,67	1,88	65,7	19,0
Marmovichskaya - 2	3,08	3,34	0,22	59,9	4,7
Vishanskaya - 18	2,76	3,28	0,48	58,8	9,25
Krasnoselskaya - 213	3,08	3,19	0,04	57,0	2,0
Drosdovskaya - 1	3,08	3,12	0,04	55,9	0,74
Osovetskaya - 1	2,70	3,34	0,81	59,9	11,2
Zolotuchinskaya - 1	2,90	3,80	6,44	68,0	16,6
Gorochovskaya - 2	2,77	3,41	0,82	61,0	11,8
Kamenskaya - 1	1,92	2,54	1,96	45,5	9,2
Aleksandrovskaya - 8	3,00	3,09	0,04	55,3	1,6
Liplyanskaya - 1	1,73	1,83	0,21	32,8	1,9

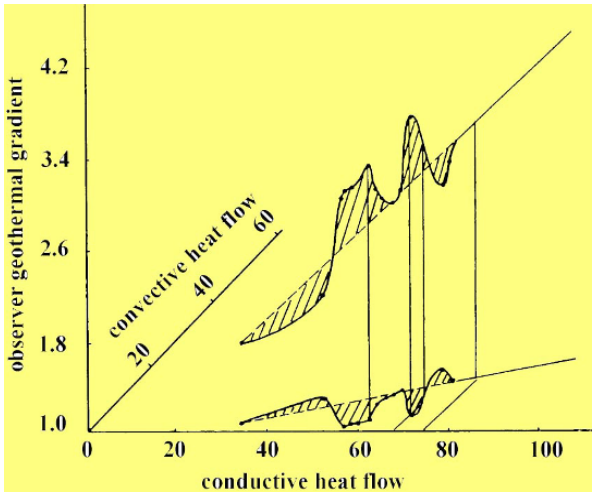


Figure 1: Pripyat depression. Geothermal gradient of above-salt sediments as a function of conductive and convective heat flow components.

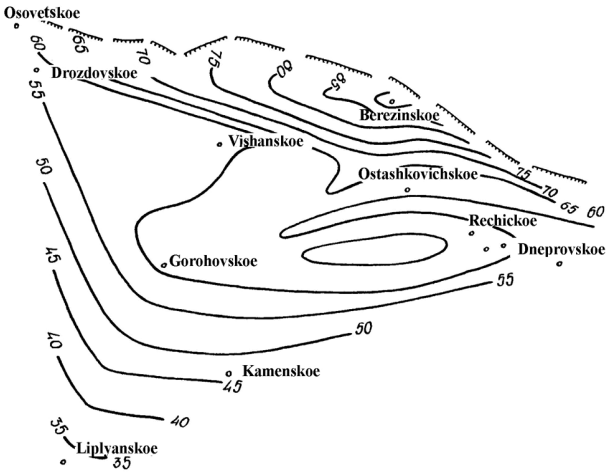


Figure 2: Pripyat depression. Scheme of distribution of conductive heat flow.

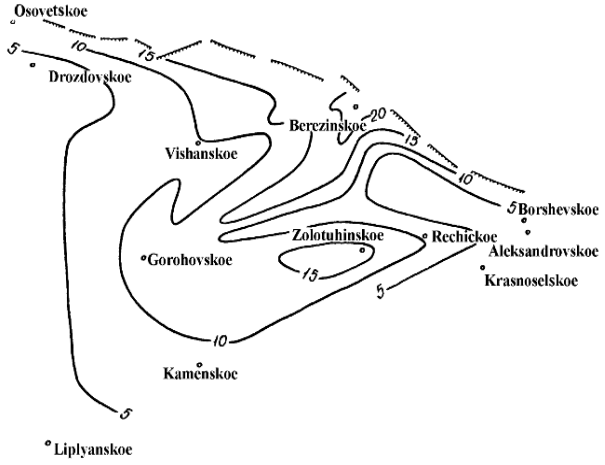


Figure 3: Pripyat depression. Scheme of distribution of convective heat flow.

To facilitate the comparison of the hydrogeological characteristics of the regions under investigation, we introduce the notion of the specific convective heat flow, $q_{cv(sp)} = q_{cv}/\Delta H$. This is an invariant parameter that describes the interval of the fluid motion ΔH and allows one to include the contribution of a unit of volume of a two phase "solid-liquid" system in the convective component of the heat flow. The specific convective heat flow, scale of which [W/m^3], may serve as a convective analogue of the value of heat generation by if a physical sense.

In figure 4 is presented a scheme of the distribution of the fluid motion rates for the Pripyat depression. The fluid motion rates for the areas under investigation varied from 0.04cm/year to 1.96 cm/year. Information about the conductive and convective components of the heat flow may be applied to the evaluation of oil/gas prospects in abyssal structures using geothermal data. We have calculated values of heat flows for regions under investigation. Some of these results are in part presented in Khodyreva (1983), (1998), (2000), (2002) and (2005).

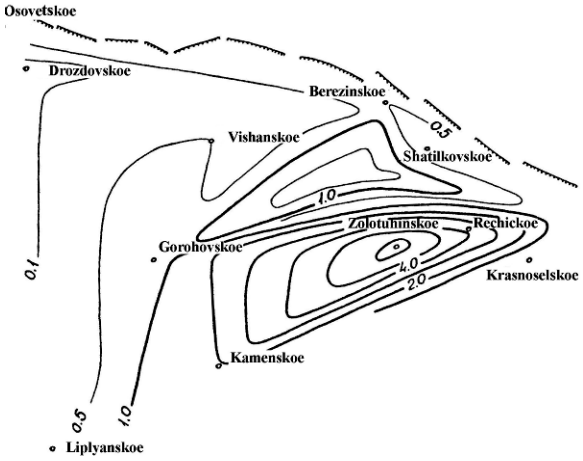


Figure 4: Pripyat depression. Scheme of distribution of the fluid motion rate.

The relation of q_{cd} and q_{cv} influences the migration of hydrocarbons in a heterogeneous geothermal field. Differences in the conductive components of the heat flow for oil-gas-formation zones and oil-gas-accumulation zones can cause a horizontal temperature gradient, which would make distant lateral migration probable. In these conditions, the vertical migration apparently relates to the convective component q_{cv}.

3. EXPERIMENTAL INVESTIGATION OF HEAT-AND-PHYSICAL PROPERTIES ROCKS. HEAT CONDUCTIVITY AND THERMAL CAPACITY

Evaluation of the heat flow is impossible without information on the thermal properties of rocks, information on 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 in elemental composition, but with a different porosities, has allowed us to form quantitative connections between porosity and the heat-and-physical properties of rocks in a temperature range from 25 to 300°C. As the table 2 shows, porosity changes from 6.77 % up to 17.03 %. Studied samples were made out of natural rocks taken from borehole №1166, located in the Demkinsk oil deposit (Russia), from 1200м to 1300м of depth. The samples were where given the shape of cylinders with diameter of ~15 mm and height ~5мм, so that they could be used in the experimental apparatus (Measuring Instrument - λ - 400). This measuring instrument is intended for mass definitions heat-and-physical parameters by a method of monotonous heating (a regular mode of type

2). The regular mode of type 2 allows users to receive at once from one experiment the temperature dependence of the investigated parameter in a temperature range from –125°C up to +400°C (with step in 25°C). In our experiment, samples were monotonously heated up from room temperature to 175°C. This upper temperature limit was chosen because, in the studied substance, there are irreversible processes at higher temperatures, owing to this the received results can appear insufficiently exact. The results of experiment are presented in the table 2.

Graphs of heat conductivity's dependence on temperature for samples №112 (porosity m = 9.77 %), №3 (m = 10.5 %) and №98 (m = 11.77 %) are presented on fig.5. As the figure shows, the heat conductivity of samples decreases as temperature rises, as is characteristic of limestone (Sidorov, Duchkov, 1989). Similar dependences are observed for other samples, and these results are presented in table 2.

It must be noted, that samples with smaller porosity possess higher heat conductivity.

The influence of temperature on rocks' heat conductivity (λ) and temperature conductivity (a) is due to the character of rocks' structure and a parity of crystal and amorphous phases in that structure. For rocks, having mainly a crystalline structure, heat conductivity and temperature conductivity decrease at temperatures higher than the Debye temperature. In porous multiphase environments and the rocks – collectors, on which pressure operates, a number of factors influence the temperature dependence of λ. These factors are the following: type of saturating fluid; thermal expansion of mineral grains and other phases, which results in deformation of rocks; change in physic-mechanical properties of solid and liquid phases upon heating, including phase transitions, etc. The density of a mineral lattice decreases with increasing of temperature and an increase in fracturing. It is connected to the non-uniform thermal expansion of components of the multiphase environment. Decrease of mineral lattice density and increase of fracturing worsen thermal contacts between components of the multiphase environment. The process results, basically, in a decreasing heat conductivity and temperature conductivity with increasing temperature. It must be noted that the influence of temperature on λ and a, as a rule, is more important than pressure. For water-saturated and the oil-saturated rocks, heat conductivity decreases with temperature more intensively than for dry (gas-saturated) rocks (Lipaev, Gurevich, 1993, 2001). The dependence of heat conductivity on porosity is presented in fig.6 for a temperature of 150°C.

Table 2

Samples №	Porosity %	Heat conductivity, W/(м×K) 50°C	75°C	100°C	125°C	150°C
113	6.77	1.83	1.71	1.74	1.73	1.78
112	9.77	2.18	2.01	1.80	1.79	1.70
3	10.50	1.81	1.71	1.72	1.69	1.66
98	11.77	1.95	1.77	1.71	1.65	1.62
1	12.80	1.59	1.47	1.50	1.48	1.50
115	13.88	1.71	1.48	1.51	1.47	1.45
2	16.20	1.54	1.44	1.43	1.41	1.38
107	17.03	1.71	1.53	1.58	1.53	1.52

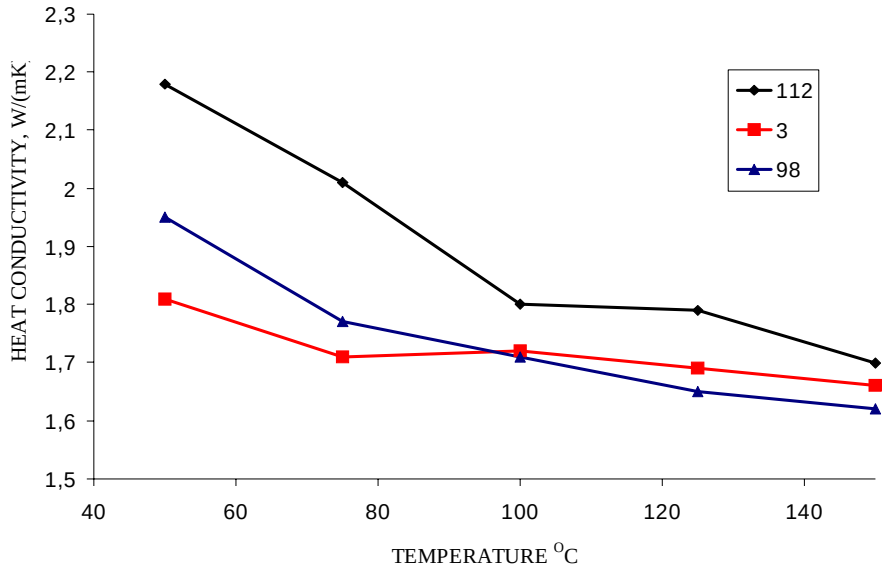


Figure 5: Graphs of heat conductivity dependence from temperature.

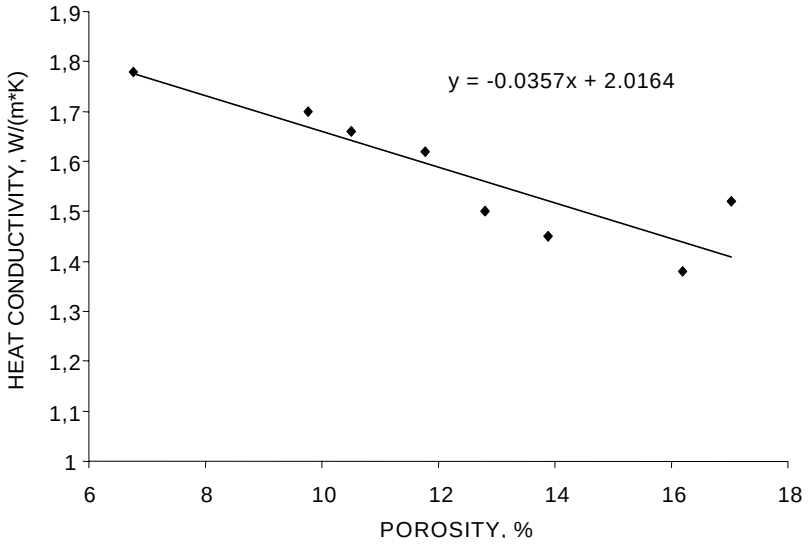


Figure 6: Dependence of heat conductivity from porosity for temperature 150°C.

This dependence is expressed as a first approximation by a linear function. The similar character of heat conductivity dependence on porosity has been noted in the literature (Lipaev, Chisamov, Gurevich, 1999, 2001). We have found that the following equation describes the dependence of heat conductivity on temperature:

$$y = -0{,}0357 + 2{,}0164$$

where ***y*** and ***x*** are heat conductivity and temperature.

In contrast to heat conductivity, a functional dependence between a thermal capacity and porosity is not established in the literary data (Berman, 1979, Babaev, 1987, Dobrynin, 1991, Lipaev, 2001). However, from the equation of transfer phenomena,

$$\lambda = \frac{1}{3}\rho C_v V l$$

(it is apparent that heat conductivity and a heat capacity are directly proportional)

where *Cv*, ρ, *V*, and ***l*** are specific heat capacity, density, speed of movement, and length of free run for a phonon.

Therefore, it is possible to assume that the heat capacity should be connected with porosity. We have made an attempt to establish experimentally a functional dependence of specific heat capacity on porosity. Studied samples were made from the same natural rocks, that is limestones taken from borehole №1166 of the Demkinsk oil deposit, as in experiments for the temperature and porosity dependence of heat conductivity. As in the previous case, the samples are in the form of cylinders with diameters of ~15 mm. However, their height, ~10мм, is that necessary for use in the experimental apparatus (Measuring Instrument – C – 400), an instrument that is intended for the study of the temperature dependence of specific heat capacity for solid bodies, liquids, and loose and fibrous materials. Results of experiment are a definition of the heat capacity of limestone with porosity from 10.5 % up to 17.47 % and in a temperature range from 50°C up to 150°C, the results are shown in table 3.

Graphs of heat capacity's dependence on temperature for samples №98 (m = 11.8 %), №1 (m = 12.8 %) and №2 (m = 16.2 %) are presented on fig.7. As the figure shows, a connection between heat capacity and temperature is observed: the heat capacity of the samples increases with increasing temperature, as is characteristic for limestone (Sidorov, Duchkov, 1989). We the following equations describe the dependence of heat capacity on temperature:

$$y = -0.0023x^2 + 1.4811x + 851.8 \text{ (m = 11.8\%)}$$

$$y = -0.0051x^2 + 2.1366x + 766.0 \text{ (m = 12.8\%)}$$

$$y = -0.0040x^2 + 2.0760x + 713.4 \text{ (m = 16.2\%),}$$

where *y* and *x* are heat capacity and temperature. Similar dependences are observed for the other samples and these results are presented in table 3. Also it is possible to establish from figure 7 that samples with smaller porosity possess higher heat capacity. The dependence of heat capacity on porosity is shown in figure 8 at 150°C. It is described by the equation

$$y = 3.683x^2 - 123.43x + 1961.6$$

where ***y*** = heat capacity and ***x*** = porosity.

Since a similar dependence is not observed in the literature, we have checked our results at other temperatures. The established dependence holds true for these temperatures too. For temperatures 200, 250 and 300°C, equations of correlation have a similar character. As a first approximation, the established connection between heat capacity and porosity can be described by the empirical equations:

$$c = 2.86m^2 - 100.04m + 1836.5 \quad T = 200^\circ C$$

$$c = 2.48m^2 - 87.80m + 1776.9 \quad T = 250^\circ C$$

$$c = 2{,}48m^2 - 87.79m + 1789.9 \quad T = 300^\circ C$$

It is necessary to note that the derived dependences require further experimental research and theoretical substantiation. The practical importance of the derived results consists in that they give an independent indirect method for evaluating rocks' porosity using a heat capacity measurement made by precise physical devices.

Table 3

Samples №	Porosity %	Heat capacity, C (J/kg·K) 50°C	75°C	100°C	125°C	150°C
3	10.5	823	878	901	902	931
98	11.8	919	950	984	992	1026
1	12.8	859	897	935	944	974
115	13.9	878	904	927	917	958
2	16.2	805	850	884	903	938
100	17.5	834	855	863	890	924

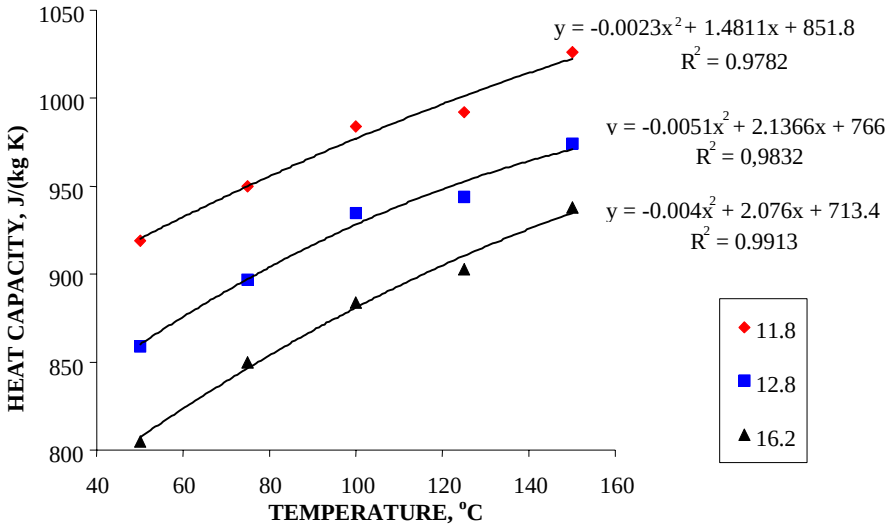


Figure 7: Graphs of heat capacity dependence from temperature.

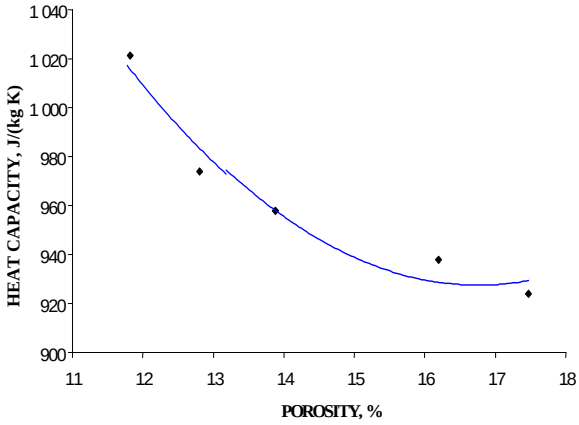


Figure 8: Dependence of heat capacity from porosity temperature 150° C.

4. CONCLUSIONS

We carried out experimental temperature measurements in more than 400 long-standing deep boreholes located in Russia, Ukraine and other regions. The depths of measuring were of 500 to 3500 m, at intervals from 0.5 to 5 m, and error no more than 0.01-0.05˚C. We introduced the quantitative relationship of hydro-geological characteristics with geothermal parameters for sedimentary basins of oil-gas accumulation areas. For the example of the Pripyat depression (Belarus), we developed the method of separation of conductive and convective components of the heat flow, were defined velocities of fluid motion and is given the quantitative estimation of hydro geological parameters by temperature measurements. As the comparison of the conductive and convective components of the heat flow shows, q_{cv} may reach 30% of q_{cd}. Therefore, in the influence zone of a hydro-geological factor, calculating q according to Fourier's law may produce an error of 30% relative to the real heat flow value. For the comparison of the hydro-geological characteristics of the regions under investigation, we introduced the notion of specific convective heat flow, $q_{CV}(sp) = q_{CV}/\Delta H$, which is an invariant in the interval of the fluid motion ΔH and allows one to take into account the contribution of a unit of volume of the two phase "solid-liquid" system to the convective component of the heat flow. We experimentally investigated the heat conductivity and heat capacity of natural rocks, specifically limestone's characteristics in the temperature range of 25° to 300°C. Our investigations of the performances of limestones with different porosities have shown that the nature of heat conduction and heat capacity change does not rule out amorphous phases. Thus, these rocks can possess plastic properties and apply for the role of depth covers, which is necessary for the preservation of oil and gas deposits at great depths. We have experimentally established a connection between specific heat capacity and porosity for limestone in the temperature range 25 – 300°C and also have offered empirical equations describing this dependence.

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