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Complex Detailed Investigations of the Thermal Properties of Rocks on the Basis of a Moving Point Source

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A new method is described for the detailed investigation of thermal diffusivity and thermal conductivity in rocks which is based on the principle of a moving point source of energy, and which guarantees high efficiency and accuracy of measurements. The distinctive features of the method include its noncontact character, the continuous investigation of the sample's thermal properties along a selected surface direction, as well as the possibility of conducting measurements on core samples without their mechanical processing.

Problems of investigation into the thermal regimes of the earth's interior are closely connected with the carrying out of bulk measurements of the thermal properties of rocks—thermal diffusivity and thermal conductivity [1].

The current methods and means for the complex determination of thermal diffusivity and conductivity, which are based on laws governing the nonstationary process of heat conduction [2, 3], have not found wide applications to the bulk measurements of thermal diffusivity and conductivity in rocks. This is a result of their low accuracy due to the impossibility in the majority of cases to allow for or to eliminate the effect of thermal resistance on the sample's surface from the measurement results, as well as the poor representation in the measurement results that characterize only small areas of the rock samples, which are essentially inhomogeneous. In addition, for the investigation of the thermal properties of rocks, in the majority of well-known measurement methods, laborious mechanical processing of the samples is necessary before measurement, including the thorough preparation of the sample surfaces, preparation of the apertures for the arrangement of heaters and temperature detectors, etc. In many cases (for example, for the investigation of unique samples) the mechanical processing of samples, leading to their partial or complete destruction, is objectionable.

In principle, the new possibilities permit a new approach to the measurement of the thermal properties of solid bodies, based on the application of a noncontact moving point source of thermal energy and noncontact recording of the temperature of the investigated bodies in a quasistationary heating regime [4].

The theory of this method is based on the consideration of the temperature field of a semiinfinite body, heated by a moving energy source. For the heating of a semiinfinite solid body by a moving point source of thermal energy moving relative to the body with a constant velocity, the steady temperature field of the body in a moving system of coordinates, whose onset is in agreement with the energy source, is described by the relation [4]

$$\theta(x, y, z) = \frac{q}{2\pi\lambda R}\exp\left(-\frac{vx}{2a}-\frac{vR}{2a}\right), \qquad (1)$$

where (x, y, z) is the excess temperature of the body at the point with coordinates (x, y, z) in the moving coordinate system (Fig. 1), q is the strength of the point source of energy, λ is the thermal conductivity of the body, a is the thermal diffusivity of the body, v is the movement velocity of the source relative to the body, $R = \sqrt{x^2+y^2+z^2}$ is the distance from the point source of energy on the surface of the body to the point of temperature recording.

The regime of measurement of the excess maximum temperature of the surface of a semiinfinite body heated by a moving point source of energy, at a point which is moving with the velocity of the source following the source on a line of heating (Fig. 1, point A), that is for $y = 0$, $x < 0$, was utilized in the method described in [4] for the determination of thermal conductivity of rocks. In this regime, the recorded excess maximum temperature of the body's surface, in the case when the strength of the energy source and the base of measurements $|x|$ are constant, depends only on the thermal conductivity of body.

For the complex determination of the thermal properties of an investigated body, two regimes for the recording of the excess temperature of its surface are possible: 1) recording of the temperature at a point which is not moving with respect to the body (Fig. 1, point B); 2) recording of the temperature at a point which is moving with respect to the body with a velocity equal to the velocity of the energy source, on a line, parallel to the line of heating of the body (Fig. 1, point C).

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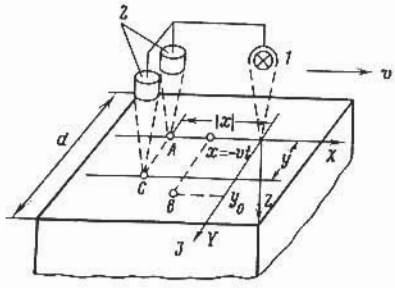

Fig. 1. Scheme of the arrangement of the energy source and the temperature gauges relative to the investigated body: 1) point source of energy, 2) temperature gauges, 3) investigated body, v) movement velocity of the energy source and the temperature gauges relative to the body, t) time after transit by the source of the projection of point B onto the axis OX, d) width of sample.

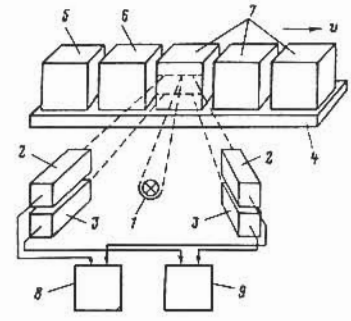

Fig. 2. Functional scheme of the laboratory apparatus: 1) source of thermal energy; 2, 3) two-channel radiometers; 4) mobile platform; 5, 6) reference samples; 7) investigated samples; 8, 9) two-channel analog recorders.

We will examine the first case. Let point B, at which is recorded the process of the change in the temperature of the body's surface in time, be located a distance from the line of motion of the source on y_0. Then, assuming $x = -vt$ (Fig. 1), differentiating (1) in time and equating the derivative to zero (that corresponds to the condition of reaching the maximum of excess temperature at point B), we obtain following formulas for the determination of thermal diffusivity and thermal conductivity of the body:

$$a = \frac{(v\tau)^2 + y_0^2 - v\tau\sqrt{(v\tau)^2 + y_0^2}}{2\tau}, \qquad (2)$$

$$\lambda = \frac{q}{2\pi\theta_M\sqrt{(v\tau)^2 + y_0^2}} \exp\left(1 - \frac{y_0^2}{2a\tau}\right), \qquad (3)$$

where τ is the interval of time after the transit of the energy source across the projection of point B on the axis OX (line of motion of the source) to the moment of reaching maximum excess temperature at the point B; θ_M is the maximum value of excess temperature of the body at point B.

Thus, the thermal properties of the investigated body may be determined by known values of q, v, and y_0, measuring the maximum value of the excess temperature θ_M at the data point on the surface of the body and the corresponding interval of time τ for the reaching of the maximum temperature.

A deficiency of this method is the necessity to measure a large number of parameters which differ in their physical nature (q, y_0, v, τ, θ_M), which complicates the measurement processes and reduces the accuracy of the obtained results.

In addition, the measured values a and λ characterize only the diagnosed region of sample. The necessity for the transfer of the region of temperature measurement from sample to sample in proportion to moving the energy source also complicates the process of measurements and reduces its efficiency.

We will consider the second case, when recording of the excess maximum temperature is accomplished at a point moving following the energy source on a line parallel to the line of heating of the body, with the same velocity as the source (Fig. 1, point C). For this, the recorded temperature of the body is determined by relation (1), in which one must set $z = 0$, $y \neq$ const 0, $x =$ const < 0. From relation (1) it follows that if in the process of measurements the strength q and velocity v of movement of the energy source are constant, as well as the base of measurements $|x|$ and the distance R from the source to the temperature recording point of the body's surface, then for a known thermal conductivity λ of the body, recording excess temperature depends only on its thermal diffusivity.

The magnitudes q, v, x, and R which are subject, in agreement with (1), to measurement for the determination of the thermal diffusivity of the body, enter into relation (1) in the form of the combinations $q/2\pi R$ and $v(R+x)/2$. It is therefore appropriate, along with the measurement of the separation of each of the indicated magnitudes, to determine their combination at once. It is possible to accomplish this operation by including two reference samples with known thermal properties in the series of the sequentially heated investigated samples, and measuring the excess temperatures of the heated surfaces not only in the investigated samples but in the references.

In the examined regime of measurements, the recorded excess maximum temperatures of the surface of each of the investigated samples and both

references are determined, in agreement with (1), by relations

$$\theta_{OBR}=\frac{q}{2\pi\lambda R}\exp\left(-\frac{vR}{2a}-\frac{vx}{2a}\right), \quad (4)$$

$$\theta_{ET1}=\frac{q}{2\pi\lambda_{ET1}R}\exp\left(-\frac{vR}{2a_{ET1}}-\frac{vx}{2a_{ET1}}\right), \quad (5)$$

$$\theta_{ET2}=\frac{q}{2\pi\lambda_{ET2}R}\exp\left(-\frac{vR}{2a_{ET2}}-\frac{vx}{2a_{ET2}}\right), \quad (6)$$

where θ_{OBR}, θ_{ET1}, θ_{ET2} are the excess maximum temperatures respectively of the investigated sample, and the first and second references on a line parallel to the line of heating of the bodies; λ, λ_{ET1}, λ_{ET2} is the thermal conductivity respectively of the investigated sample, and the first and second references; a, a_{ET1}, a_{ET2} is the thermal diffusivity respectively of the investigated sample, and the first and second references.

From relations (4) - (6), which express the combinations $q/2\pi R$ and $v(R+x)/2$ in terms of the excess maximum temperatures and the known thermal characteristics of the reference samples, we obtain a standard working formula for the thermal diffusivity of an investigated sample:

$$a=\frac{a_{ET1}\ln\frac{\lambda_{ET1}\theta_{ET1}}{\lambda_{ET2}\theta_{ET2}}}{\ln\frac{\lambda_{ET1}\theta_{ET1}}{\lambda_{ET2}\theta_{ET2}}+\frac{a_{ET2}-a_{ET1}}{a_{ET2}}\ln\frac{\lambda\theta_{OBR}}{\lambda_{ET1}\theta_{ET1}}} \quad (7)$$

We note that since only the ratios of the excess temperatures of the samples and the references enter into formula (7), then for the determination of thermal diffusivity by the described method, the requirement for the measurement of the absolute values of these temperatures is absent. It is sufficient, provided that there is linearity of the temperature gauge, to utilize in formula (7) levels of the outgoing signal of the gauge proportional to the excess temperatures.

In the obtained working formula (7) it is assumed that for determination of the thermal diffusivity of the sample, its thermal conductivity is known. However, in practice, in the investigation of rock samples, as a rule both of the indicated parameters are unknown and subject to determination. Therefore, for complex investigations of the thermal properties of rock samples by the considered measurement regime, when the recording point of the excess surface temperature of the heated bodies is displaced on the straight, parallel line of heating, it is necessary to combine the measurement regime for thermal conductivity described in [4]. In that measurement regime, the temperature recording point is moved on the line of heating, and with the presence of the two references, the thermal conductivity of the investigated samples will be determined by the following formula:

$$\lambda=\frac{\lambda_{ET1}\theta'_{ET1}+\lambda_{ET2}\theta'_{ET2}}{2\theta'_{OBR}}, \quad (8)$$

where θ'_{OBR}, θ'_{ET1}, θ'_{ET2} are the excess maximum temperatures of the surfaces, respectively, of the investigated sample, and the first and second references on the line of heating of the bodies by the energy source. The use of two references for the determination of thermal conductivity enables one to significantly increase the accuracy of the measurements.

Thus, the proposed method for the complex determination of thermal properties of rocks includes the heating of a series of successively ascertained investigated samples and two references by a mobile point source of energy which is moving relative to the heated bodies with a constant velocity, and the recording with a constant measurement base of the excess maximum temperatures of the surfaces of the heated bodies along two lines, one of which coincides with the line of heating, and the second of which is parallel to it (Fig. 1). Substituting the measured excess temperatures of the bodies, as well as the known thermal conductivity and diffusivity of the two reference samples into formulas (7) and (8), determines the thermal characteristics of each of the investigated samples.

The laboratory apparatus, which provides the complex determination of thermal properties of rocks by the proposed method, contains a noncontact focused energy source, two two-channel radiometers, intended for the noncontact recording of the excess maximum temperature of the surface of heated body by electromagnetic radiation, moved with the aid of an electrically driven mobile platform, on which the reference and investigated samples are arranged, and two analog recorders. An operational scheme of the laboratory apparatus is shown in Fig. 2.

We used a continuous operation laser beam with a radiation wavelength of 10.6 μm and power up to 5 W as an energy source which is closest to a point source in its characteristics. Noncontact recording of the surface temperature of the heated samples was accomplished by highly sensitive laboratory radiometers of original construction, which recorded thermal radiation on a wavelength band of 2 to 20 μm. The outgoing signals of the radiometers, which characterized the excess temperature of the heated surface of the investigated samples and references, were recorded with the aid of self-recording instruments.

In practice, the process of determination of thermal diffusivity and conductivity of rock samples is accomplished as in the following example. The investigated samples (up to 20 samples) and two reference samples are mounted to the mobile platform. In the process of uniform motion of the platform with the samples relative to the laser and radiometers, the laser beam successively heats the samples in a straight line and the radiometers record the excess maximum temperatures of the sample surfaces and references on two

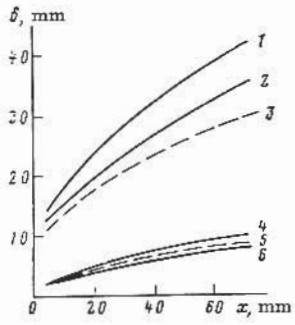

Fig. 3

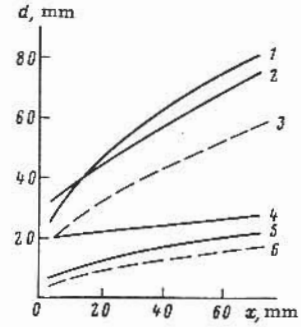

Fig. 4

Fig. 3. Graphs of the dependence of the sample thickness δ, ensuring that the systematic error in the determination of thermal diffusivity δa is no more than 1%, on the parameters of the measurement regime: 1) $v/a = 5 \cdot 10^2$ m^{-1}, $y = 3 \cdot 10^{-2}$ m; 2) $v/a = 5 \cdot 10^2$ m^{-1}, $y = 10^{-2}$ m; 3) $v/a = 5 \cdot 10^2$ m^{-1}, $\delta\lambda = 1\%$; 4) $v/a = 5 \cdot 10^3$ m^{-1}, $y = 3 \cdot 10^{-3}$ m; 5) $v/a = 5 \cdot 10^3$ m^{-1}, $\delta\lambda = 1\%$; 6) $v/a = 5 \cdot 10^3$ m^{-1}, $y = 10^{-2}$ m.

Fig. 4. Graphs of the dependence of the sample width d, ensuring that the systematic error in the determination of the thermal diffusivity $\delta\lambda$ is no more than 1%, on the parameters of the measurement regime: 1) $v/a = 5 \cdot 10^2$ m^{-1}, $y = 3 \cdot 10^{-2}$ m; 2) $v/a = 5 \cdot 10^2$ m^{-1}, $y = 10^{-2}$ m; 3) $v/a = 5 \cdot 10^2$ m^{-1}, $\delta\lambda = 1\%$; 4) $v/a = 5 \cdot 10^3$ m^{-1}, $y = 10^{-2}$ m; 5) $v/a = 5 \cdot 10^3$ m^{-1}, $y = 3 \cdot 10^{-3}$ m; 6) $v/a = 5 \cdot 10^3$ m^{-1}, $\delta\lambda = 1\%$.

parallel lines, one of which is coincident with the line of heating. Two successive signals will be recorded on the plotting strip of self-recording instruments, one of which corresponds to the excess maximum temperature of the sample surface on the line of their heating by the laser beam, while the second is on a parallel line. Substitution of the levels of signals recorded by the self-recording instruments into the working formulas (7) and (8), determines the thermal diffusivity and conductivity of each of the investigated samples. After arrangement of the new series of investigated samples on the mobile platform, the apparatus is prepared for a subsequent process of measurements, in the course of which displacement of platform with samples occurs in the reverse direction. In practice, it is possible to accomplish the substitution of each of the investigated samples by a sample of a new series immediately after the output of the data sample from the field of view of radiometers, that is, after the conclusion of recording of the excess temperature of its surface. Hence, it is not difficult to halt the apparatus for the substitution of one series of samples for another. This makes it possible to conduct measurements continuously.

The developed method and apparatus provide the determination of thermal diffusivity of rock samples in the range $(1 - 50) \cdot 10^{-7}$ m^2/s with error no greater than 8%, and thermal conductivity in a range of 0.5 to 20 W/m K with error no greater than 5%. The duration of the measurement process of a series of 10 to 15 investigated samples which are each 40 to 80 mm in length, with a platform displacement velocity of $5 \cdot 10^{-3}$ m/s does not exceed 5 to 7 min. This permits one to conduct complex investigation of the thermal properties of up to 500 samples per working shift.

For examination of systematic errors in the described method we conducted a theoretical analysis of the effect on the measurement results of the difference of a real energy source (laser beam) and a point source, as well as the effect of the sizes of the investigated samples. The results of analysis showed that it is possible to neglect the difference between a real and point energy source, if the distance of the area of excess temperature recording from the spot where the sample's surface is heated by the energy source exceeds several diameters of the heating spot. So, for example, for a base of measurements $|x| =$ 15 mm and a magnitude of displacement of the excess temperature recording region of the body's surface from the line of heating $y = 6$ mm, the systematic error in the determination of thermal diffusivity of a sample of marble ($a = 1.2 \cdot 10^{-6}$ m^2/s) for a heating spot of 3 mm does not exceed 2%. Thus, by knowing the assumed range of values of thermal diffusivity in the investigated rock samples, it is possible in practice through selection of a corresponding measurement regime to eliminate the error due to the inaccuracy of a real energy source.

Relations (7) and (8) were obtained for a semiinfinite solid body, rather than for the investigation of rock samples, which have fully determined finite sizes. In practice there are important questions on the effect of the samples' boundaries on the results of measurements and on

the minimum sample sizes which enable one to neglect the effect of the indicated boundaries. We used as a criterion for the smallest permissible sizes of investigated samples a condition which included that the systematic error in the determination of thermal diffusivity should not exceed 1%. In Fig. 3 we show the dependences of the sample thickness δ, for which systematic error in the determination of its thermal diffusivity δa does not exceed 1%, on the parameters of the measurement regime—the bases of measurements $|x|$, the displacement of the temperature recording point of the body's surface on the line of its heating y, and the ratio of the sample's movement velocity to its thermal diffusivity v/a. In Fig. 4 we show analogous dependences for the width of the sample d, for which systematic error in the determination of its thermal diffusivity does not exceed 1%. For comparison, in Figs. 3 and 4, we show by dashes the dependences of thickness and width of the sample, for which the systematic error in the determination of the sample's thermal conduction does not exceed 1%.

From Fig. 3 it follows that the greater the displacement of the temperature recording point of the body's surface from the line of heating, the thinner the investigated sample may be, while a decrease in the ratio v/a (that is, a decrease of the movement velocity of the sample or an increase of its thermal diffusivity) leads to an increase in the minimum permissible thickness of the sample. In addition, from Fig. 3 it follows that for small v/a, the examined method demands a more rigorous minimum permissible sample thickness, than does the method described in [4] for the determination of thermal conductivity of rocks. For large values of the relation v/a ($5 \cdot 10^3 - 10^4$ m^{-1} and more) the minimum permissible sample thickness is established on the basis of combined analysis of the dependences presented in Fig. 3 from the point of view of providing minimal errors in the determination of thermal diffusivity and conductivity. For example, for $|x| = 20$ mm, $v = 5 \cdot 10^{-3}$ m/s, $a = 10^{-6}$ m^2/s, and $y = 5$ mm, the minimum sample thickness for the determination of thermal diffusivity comes to 4.5 mm, while for the determination of thermal conductivity it is 4.7 mm. Thus, in the considered case for the method of complex determination of thermal properties, it is necessary that the sample thickness be no less than 4.7 mm.

Analysis of dependences presented in Fig. 4 shows that for small values of the ratio v/a, on the order of $10^2 - 5 \cdot 10^2$ m^{-1} (the case of small movement velocities and large thermal diffusivities of the samples), with increase of displacement y of the temperature recording point on the line of heating, the minimum allowed width of the sample is decreased. For large v/a this dependence is inverted, that is, the greater the magnitude of y, then the wider the sample should be. For example, for $|x| = 20$ mm, $v = 5 \cdot 10^{-3}$ m/s, $a = 10^{-6}$ m^2/s, and $y = 3$ mm, the minimum width of sample should be no less than 12.8 mm, while for $y = 10$ mm, it should be no less than 22.3 mm. We note that the examined method for the complete determination of thermal properties of rocks for every measurement regime shows that the minimum allowable width of the sample is a more rigorous requirement than the method of determination of thermal conductivity [4].

The dependences presented in Figs. 3 and 4 also permit one to judge the sizes of the sample area, whose thermal properties are determined as a result of measurements.

Instability in the strength of the energy source and instability of the movement velocity of the platform with the samples are fundamental sources of random errors in the data method, if we do not consider the noise of the apparatus. If, in the determination of thermal conductivity, random error which results from instability in the strength of the energy source, is completely determined by the magnitude of this instability [4], then for the determination of the thermal diffusivity, it depends significantly on the parameters of the measurement regime. In Fig. 5 we show the dependences of random error in the determination of the thermal diffusivity of the

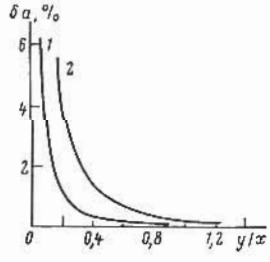

Fig. 5

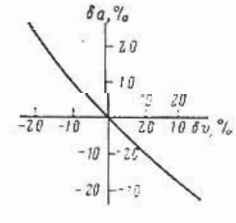

Fig. 6

Fig. 5. Graphs of the dependence of random error in the determination of thermal diffusivity $\delta\lambda$ on the parameters of the measurement regime for instability in the strength of the energy source, equal to 1%: 1) $|x| = 2 \cdot 10^{-2}$ m, $v/a = 5 \cdot 10^3$ m^{-1}; 2) $|x| = 2 \cdot 10^{-2}$ m, $v/a = 10^3$ m^{-1}.

Fig. 6. Graph of the dependence of random error in the determination of thermal diffusivity δa on instability in the movement velocity of the samples δv.

Table 1

Sample	Rock	Apparatus on the base of a mobile source		IT-λ-400
		λ_{av}, W/m·K	$\lambda_{min} - \lambda_{max}$, W/m·K	λ, W/m·K
1	Limestone	2,08	2,04–2,20	2,14
2	»	2,62	2,47–2,71	2,42
3	»	2,77	2,67–2,82	2,64
4	Dolomite	3,15	3,08–3,32	3,33
5	»	3,11	2,93–3,45	3,27
6	»	2,71	2,60–2,76	2,54
7	»	3,79	3,47–4,17	3,72
8	»	3,83	3,65–3,89	3,60
9	»	3,06	2,88–3,27	3,37
10	Phosphorite	2,73	2,68–2,80	2,60
11	»	3,47	3,30–3,61	3,62
12	»	3,76	3,34–3,87	3,37

sample δa on the parameters of the measurement regime for the amount of instability in the strength of the energy source equal to 1%. From the presented dependences it follows that for a decrease of the effect of instability in the strength of the energy source on the results of thermal diffusivity measurements, it is appropriate to increase the ratio of the amount of displacement of the temperature recording point from the line of heating to the magnitude of the base of the measurements.

The dependence of random error in the determination of thermal diffusivity δa on the instability of the movement velocity of the samples δv relative to the energy source and the radiometers is shown in Fig. 6. One should note that the magnitude of random error is completely determined by the instability of velocity and does not depend on other parameters of the measurement regime.

For recording of the bodies' temperature by the radiation method, the measurement results will depend on the coefficient of radiation and the state of the bodies' surface. Therefore, in the described method, it is specified that before measurements, a narrow band of rapid-drying matte enamel with a thickness of 10 to 15 μm, which has a radiation coefficient of approximately 1, is deposited on the working surface of the samples and the references along the selected measurement direction.

The described method does not have rigid requirements for the state of the working surface of the samples. As shown in laboratory investigations, the difference in the measurement results on polished and rough sample surfaces with a root-mean-square value of roughness of 1 mm reached no more than 5% and had a systematic character, that is, it is easily possible to eliminate it. The absence of rigid requirements for the geometric form and the surface processing quality in the investigated samples enables the effective utilization of the given method and apparatus for investigation of thermal properties of rocks directly in the core without preliminary mechanical processing. In this case, measurements are conducted on the generated core.

One of the most important qualities of the proposed method is that in distinction from existing methods for the complex determination of thermal properties in solid bodies, it permits us not only to determine the average value of these characteristics for a sample of their value in several of its areas, but it also makes it possible to conduct a direct measurement of the thermal diffusivity and conductivity of the sample along a surface direction selected on it, that is, to obtain the distribution of these parameters on the sample. In principle, this creates new possibilities for the investigation of rock samples: the detailed study of samples from the point of view of the inhomogeneity of their thermal properties, the discrimination of inclusive minerals with the determination of their thermal properties, the exposure and investigation of subsurface regions, the investigation of the effect of fracturing on the thermal properties of rocks, etc.

The developed apparatus enables us to determine the thermal characteristics of surface outcroppings in the sample of inhomogeneous areas with errors that do not exceed the above indicated values, for inhomogeneities no less than 10 × 15 mm in area (where the first dimension refers to the direction of movement). For smaller sizes of inhomogeneities, it is possible to establish only the character of the change in their thermal diffusivity and conductivity in relation to the adjoining regions of the sample. Decrease of the indicated constraint may be reached owing to increase in the concentration of the energy source (a decrease in the diameter of the heating spot), which permits one to work with a small base of measurements and to bring together the lines on which the temperature is recorded.

In the table we show a comparison of the results of thermal conductivity measurements in core samples from a well in northern Mongolia on the developed apparatus, based on the principle of a moving energy source, and on the IT-λ-400 apparatus, which was utilized for the measurement

of thermal conductivity of rocks. In the first case the measurements were conducted directly on the generated core, while in the second case they were performed on thin slices of core samples. The results of the measurements on the developed apparatus are presented in the Table by average values and the range of change in the thermal conductivity of the sample.

On the whole, as follows from the table, good agreement is observed between the results of measurements of thermal conductivity by the two indicated apparatuses. The differences at hand for a series of samples (2, 9, 12) between the measurement results, which reach 8 to 10%, may be explained by randomness in the selection of the regions of core samples, from which the thin slices were prepared for measurements in the IT-λ-400 apparatus.

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