NEW EXPERIMENTAL AND THEORETICAL BASE FOR RESERVOIR THERMAL PROPERTIES DETERMINATION AND PORE SPACE CHARACTERIZATION

[1]Popov Yu., [1]Korobkov D., [1]Miklashevskiy D., [1]Safonov S., [2]Novikov S.
[1]-Schlumberger, [2]-Russian State Geological Prospecting University

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Halifax, Nova Scotia, Canada, 4-7 October, 2010

ABSTRACT

New and complex research into thermal petrophysics includes an experimental and theoretical basis developed to determine the thermal conductivity, thermal diffusivity and volumetric heat capacity of dense and highly porous and fractured rocks at normal and formation thermodynamical conditions. The equipment used includes: (1) a set of nondestructive and contactless optical scanning instruments to record the variations of thermal conductivity and diffusivity along the inhomogeneous samples in dry and fluid-saturated states, with high precision and accuracy; (2) instruments for the measurement of rock thermal properties with simultaneous influences of temperature (up to 250 degC), pore pressure, and two components of lithostatic pressure (up to 200 MPa); (3) instruments for the measurement of linear thermal expansion coefficient; (4) instruments for fluid thermal conductivity measurements.

Our complex research provides numerous high-precision measurements on a representative collection of full size cores and core plugs. As a result of the complex application, an extended database on rock thermal properties was created and the correlations between thermal, reservoir and other physical properties were established.

INTRODUCTION

Experimental data on the thermal properties of rock are necessary when thermal processes in formations are studied. The thermal conductivity λ determines how easily heat can pass through the formation and links the heat flow density q and the temperature gradient $\partial T/\partial x$ in Fourier's law of heat conduction: $\vec{q} = -\lambda \cdot gradT$

Volumetric heat capacity C determines the quantity of heat energy ΔQ which is necessary to heat 1 m^3 of material by 1 K. The thermal diffusivity a characterizes the rate of temperature front propagation within the media during thermal transient processes. The thermal conductivity, thermal diffusivity and volumetric heat capacity are interconnected by the formula $a \cdot C = \lambda$. Data on thermal diffusivity and conductivity allows us to

determine rock thermal capacity and, if density is known, specific heat capacity also. Nevertheless, experimental data on thermal diffusivity are very poor and up-to-date methods and equipment for rock thermal diffusivity measurements are problematic—the techniques are significantly less developed than the experimental base for rock thermal conductivity measurements.

As shown by numerous theoretical and experimental studies, the thermal properties of rock depend on various factors including porosity, fracturing, mineral composition, rock structure, and the type of fluid in pores and cracks. These studies have demonstrated the significance of porosity and fracturing on rock thermal conductivity, and have shown that between these properties there exists a complicated relationship which is particularly dependent on pore space structure. Detailed data on this relationship were presented by Somerton (1992), Zimmerman (1989), Brigaud (1989), Horai (1991), and Schoen (1996). However, many serious methodical problems inhibit our understanding and limit our knowledge of thermal properties. The following problems are typical for thermal property measurements in geophysics: (1) the set of standard materials with well known thermal diffusivity is very restricted and does not cover the rock thermal diffusivity range, (2) thermal conductivity and diffusivity tensor components cannot be determined on one rock sample, (3) traditional methods and instruments have serious restrictions in their application to thermal conductivity measurements on highly porous and fractured rocks and cannot be applied to nondestructive measurements on full size cores and core plugs, (4) the measurement of thermal conductivity and diffusivity tensor components at simultaneous influences of formation temperature and pressure (with differentiation of axial, confining, and pore pressure) cannot be provided, (5) rock inhomogeneity cannot be taken into account, (6) no information about inter-laboratory tests or careful metrological investigations of developed instruments has been published, (7) experience in thermal diffusivity measurements in geophysics is much smaller than in thermal conductivity measurements, (8) the impossibility to determine the coefficient of linear thermal expansion at elevated temperatures within narrow temperature intervals (15–25 degC) does not allow the determination of a temperature dependence of the parameter within a temperature range from 20 to 250 deg C.

RESULTS

New, highly effective methods and instruments for thermal property measurement have been developed during recent years, and they have essentially improved the quality of geothermal information as a whole.

Optical Scanning Technique—Nondestructive and Noncontact Measurements on Cores at Normal Conditions

Method description

A noncontact optical scanning technique (Popov, 1997; Popov *et al.*, 1999) provides, in principle, a new approach to the study of the thermal conductivity and thermal diffusivity

of rocks. The special theoretical background of the technique was developed. The main advantages of this instrument are: (1) high precision (1.5%) and accuracy (1.5%) of measurements within the thermal conductivity range of 0.1–70 W/m K for dry and fluid-saturated samples, (2) high precision (2%) and accuracy (2%) of thermal diffusivity measurements within the range of $(0.1–5.0)\cdot10^{-6}$ m^2/s K, (3) determination of thermal conductivity and diffusivity tensor components for each rock sample under study, (4) numerous nondestructive measurements on cylindrical or flat core surfaces with no additional mechanical treatment of cores, (5) measurements that can be made on rock samples of different sizes, from 1 to 70 cm in length, (5) the thermal conductivity and diffusivity distributions along a scanning line for each sample can be recorded to detect the rock inhomogeneity, (6) the short time it takes to measure a sample (10–30 s).

The optical scanning (OS) method (Fig. 1) is based on scanning a sample's surface with a constant speed using a focused, movable heat source (2) in combination with temperature sensors (1). The sample's (5) heating level and initial temperature level are registered by

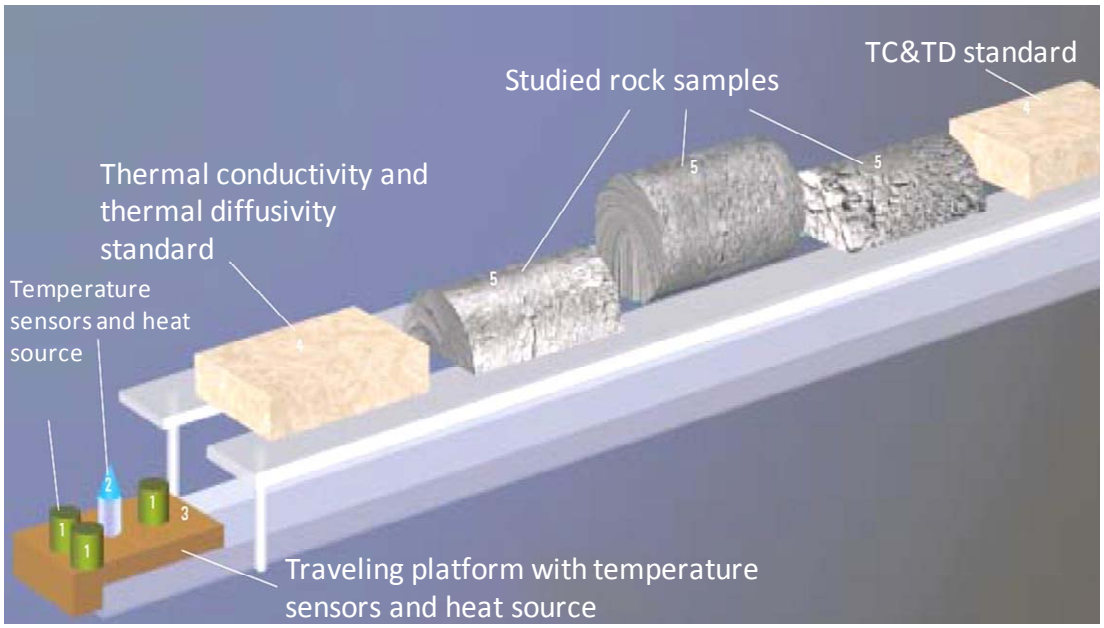

Figure 1. Optical scanning method.

infrared detectors which move along the same rock surface with the same speed that the heat spot moves. Two standard samples (4) with known thermal conductivity and thermal diffusivity are processed in the same series as the studied samples. Thermal properties are determined by comparing the heat levels of the rock samples with the heat levels of the standard samples, using the original theoretical base. Two automated (computerized) optical scanning data measurement systems were created: (1) a portable hand-held field system for precision measurements of the thermal conductivity on cores at the drilling site, (2) a laser system for precision measurements of the thermal conductivity and thermal diffusivity under laboratory conditions. Scanning along three (for the case of 3D

anisotropy) or two (for 2D anisotropy) directions provides information about the thermal conductivity tensor components.

The specific feature of OS is the ability to change the thickness of the investigated surface layer depending on the sample size and research goals. This can be done with a change in measurement regime including the speed of scanning and the distance between the heated spot and the area of temperature recording. The thickness of the core layer involved in the measurement due to heat depth penetration depends on the scanning velocity, the distance between the heating spot and the point of temperature recording, and the thermal conductivity and diffusivity values (Popov *et al.*, 1999). The layer thickness may reach 2–3 cm or more for samples with thermal conductivity exceeding 6-7 W/m K (Popov *et al.*, 1997). For the sedimentary rock collections studied on full size cores, the scanning velocity (about 4 mm/s) and the distance between the heating spot and a point of temperature recording (about 50 mm) are chosen to provide a core layer thickness roughly between 1.5 and 2 cm. A length of full size cores studied with the optical scanning instruments and the optical scanning line along the cores is usually 7-20 cm. Therefore the total rock volume involved in the optical scanning measurement for every core is 6-30 cm^3 which is comparable with this parameter for the measurements with the line source approach. A core sampling interval is chosen normally from 1 to 3 m which allows us to construct detailed thermal property logs along the wells. For core plugs the measurement regime parameters are respectively 2 mm/s and 1.0-1.5 cm, which reduces the thickness of core layer involved in the measurement to 1-1.3 cm; therefore the optical scanning measurements on core plugs are performed on both core bottoms to provide for a larger rock sample volume under study.

The signal-processing algorithm yields the effective conductivity for two perpendicular directions for an inhomogeneous layered sample. The mean level of temperature along the scanning profile is used for the determination of the thermal conductivity tensor component in the orientation coinciding with the scanning direction, and the thermal conductivity tensor component normal to the heated surface is determined as an arithmetic mean of local conductivities along the entire scanning line. Experimental studies of inhomogeneous samples consisting of up to 20 layers with thermal conductivities ranging from 1.35 to 21.0 W/m·K and thicknesses varying from 1 to 15 mm have shown that this determination of effective thermal conductivity does not differ significantly from the calculated conductivity of layered samples (Popov *et al.*, 1997). Local conductivities can be determined for grain scales as small as 7 to 10 mm.

Experimental investigation into the correlations between rock thermal conductivity, thermal diffusivity, and other physical properties.

Difficulties in measuring the thermal properties of sedimentary rocks are caused by problems with thermal contact between the heater and temperature sensor on the one hand and the rock sample on the other hand. Measurements on water- and oil-saturated rock samples had an additional serious problem because of the possible destruction of

samples at pressure, which was necessary for all previous measurement methods to improve the thermal contact mentioned. These reasons explain the situation when the experimental data on thermal conductivity of fluid-saturated sedimentary rocks and thermal diffusivity of dry and fluid-saturated sedimentary rocks were poor and contradictory, even in the most respected publications (Brigaud, 1989; Schoen, 1996). Furthermore, often thermal anisotropy of thermal conductivity and thermal diffusivity was not taken into account.

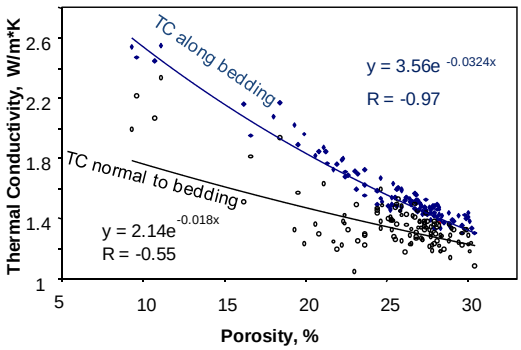

Figure 2. Correlation between TC tensor components ($\lambda_{\perp}$ and $\lambda_{\parallel}$) and porosity for dry cores from an oilfield (West Siberia).

The enhanced optical scanning technology described above allows us to start regular thermal conductivity (TC) and thermal diffusivity (TD) studies of dry and fluid-saturated sedimentary rocks, which is necessary in geothermal investigations of formations. In our research (Popov *et al.*, 2003) it was found that the thermal conductivity tensor component parallel to the bedding plane (Fig. 2) is the most important in investigations of correlations between thermal conductivity and other physical properties; therefore, we have preferentially used a corresponding component of thermal conductivity and diffusivity tensors in our new investigations.

The experimental data on the correlation between the parallel component of TC (λ_{dry}) and porosity for dry samples are combined in Fig. 3A. As the figure shows, only results for quartz sandstones and dolomites differ significantly from other rock types and are characterized by similar regression lines. Extrapolation of the TC results to a porosity value of $\Phi=0$ allows us to estimate a rock skeleton TC within a range of 2.5 to 3.1 W/m K except for Cambrian quartz sandstones with a skeleton TC larger than 6.0 W/m K, caused by large amounts of quartz in the rock (around 90%), cement composition (quartz cement), and probably by the "rigidity" of grain contacts. This is evident after water saturation, where the correlations become weaker (Fig. 3B) because of the decreasing difference between the pore fluid properties and the mineral skeleton, especially for thermal diffusivity and capacity.

Some statistical data on the thermal conductivity and porosity of cores from the Yen-Yakhinskaya scientific superdeep well (which reached a depth of 8,205 m) drilled in the Yamalo-Nenetsk autonomous region, West Siberia, Russia, are presented in Figure 4. The figure illustrates variations of thermal conductivity within different scales (from one layer to the whole well).

Figure 5 demonstrates correlations between thermal diffusivity and thermal conductivity for water-saturated rock samples. It was found that unified dependence between thermal conductivity and thermal diffusivity for all rock types studied is not linear (Fig. 5). The

average deviation of the experimental results from the regression equation established is ± 11%. The maximum deviation for the studied samples does not exceed 40% for dry rocks, and ± 15% and 55% for water-saturated rocks respectively. Dependences between thermal conductivity and thermal diffusivity for dry and water-saturated rocks are slightly different due to a significant increase in TC at water saturation (up to 100% and higher) and insignificant changes in TD which depends mainly on pore space geometry.

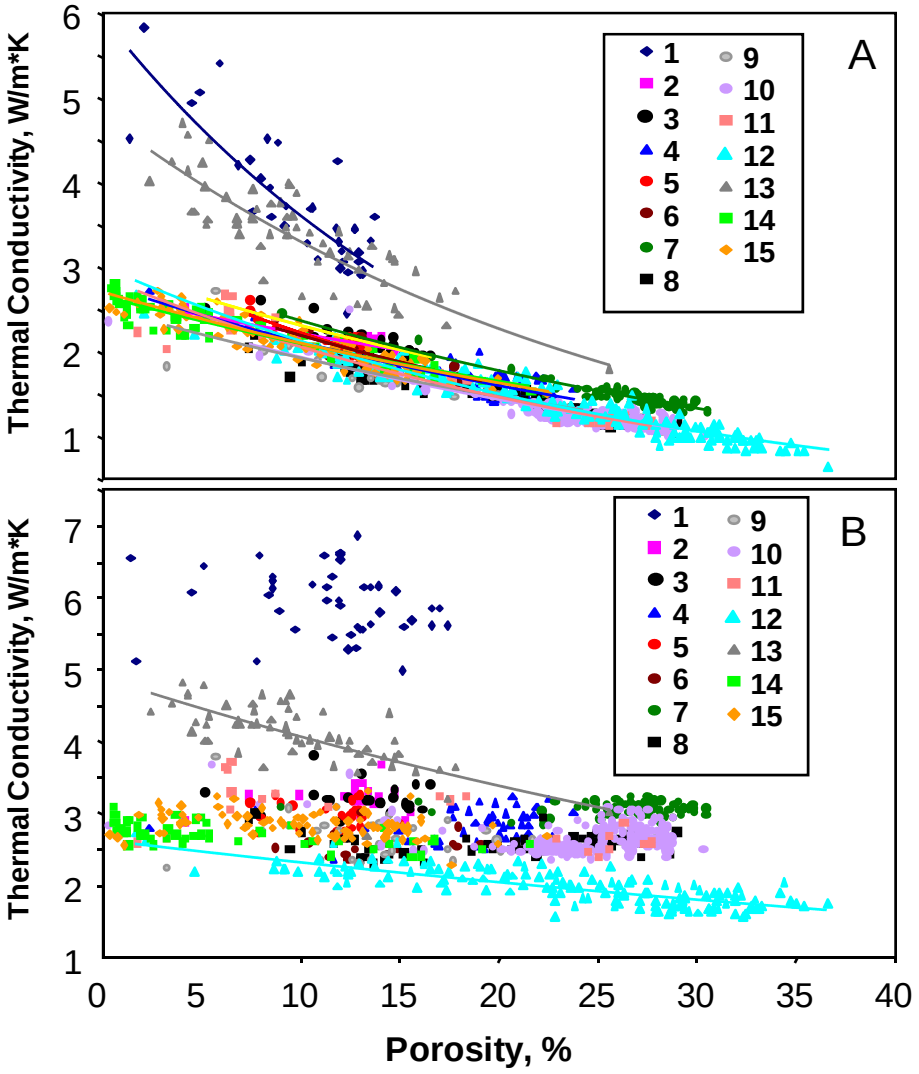

Figure 3. Correlation between dry (A) and water-saturated (B) rock and porosity.
1. quartz sandstone (quartz cement), 2. polymictic sandstone (clayey cement), 3. feldspar-quartz sandstone (clayey cement), 4. feldspar-quartz sandstone (clayey cement and mica), 5. arcosic siltstone (clayey cement), 6. feldspar-quartz siltstone (clayey cement and mica), 7. quartz siltstone (clayey cement), 8. quartz siltstone (clayey cement), 9. argillite, 10. feldspar-quartz sandstone (clayey cement), 11. feldspar-quartz sandstone (carbonate cement), 12. organogenic limestone (Tertiary), 13. dolomite, 14. algal limestone, 15. organogenic limestone (Permian).

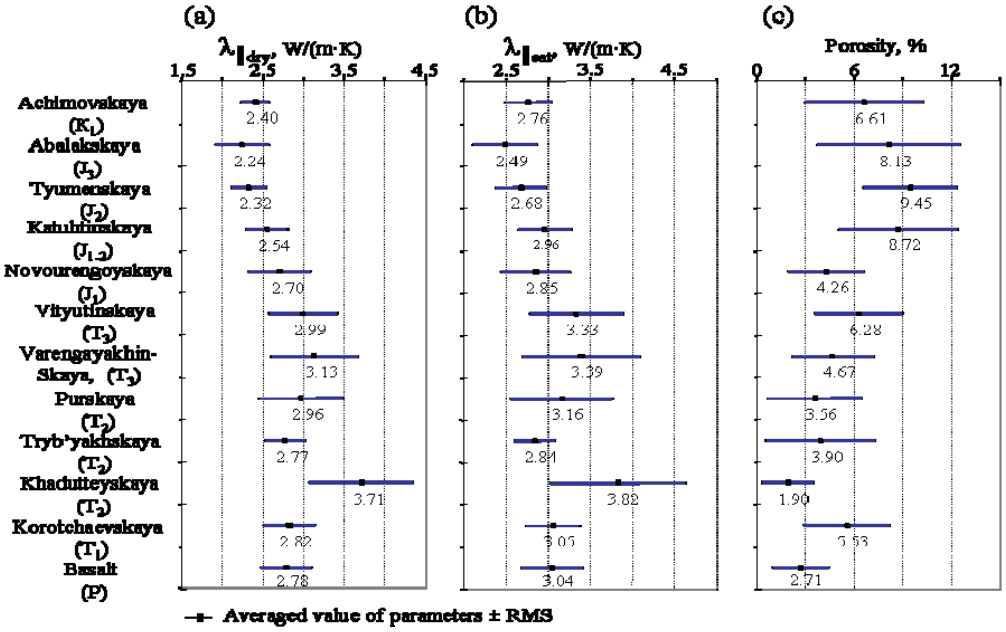

Figure 4. Thermal conductivity (TC component parallel to formation bedding, dry, and water-saturated rocks) and porosity for different formations crossed by the Yen-Yakhinskaya superdeep well.

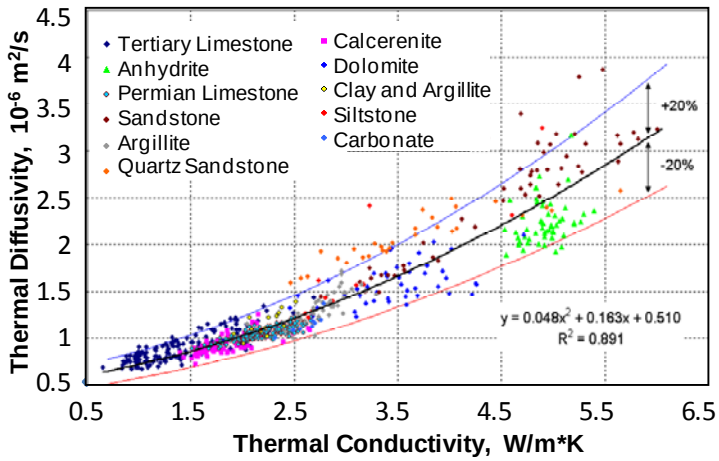

Figure 5. Correlation between thermal conductivity and diffusivity.

Instrument for the Measurements of Thermal Properties of Rocks and Minerals at Formation Pressure and Temperature

An instrument for the measurements of a rock's and a mineral's thermal conductivity and thermal diffusivity with simultaneous influence of temperature (up to 250°C), and pore pressure and two components of lithostatic pressures (up to 200 MPa) has been developed. The new experimental and theoretical approaches of a line-source method has been found to provide simultaneous measurements of TC and TD tensor components within one measurement cycle (Miklashevskiy *et al.*, 2006).

The instrument for TC&TD measurements at elevated pressure and temperature includes the following basic units: oil compressor, high pressure and high temperature chamber, manometers to control three components of pressure and PC with data acquisition system. Prior to each TC and TD measurement at elevated PT conditions, two halves of the rock sample studied should be prepared in the form of cylinders with diameter of 50 mm and height of about 25 mm. Two perpendicular platinum wires of 0.1 mm diameter jointly function as heat line sources and distributed temperature sensors are mounted between two halves of the rock samples (Fig. 6). An elastic compound is used to fill the space between the halves. Such a measuring cell provides simultaneous measurements of principal TC and TD tensor components during one PT cycle (Miklashevskiy *et al.*, 2006). The measuring pressure-temperature chamber of the instrument is shown in Fig. 7.

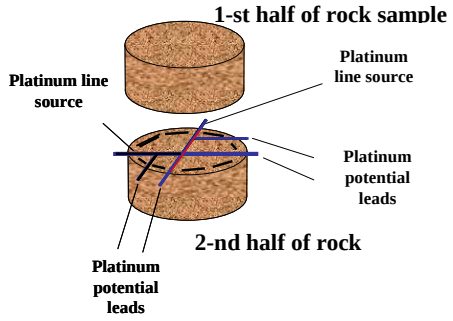

Figure 6: Measuring cell for simultaneous measurements of TC and TD tensor components at elevated PT conditions.

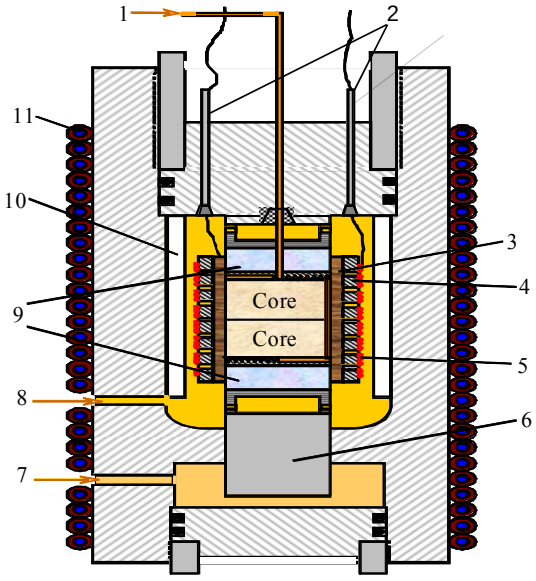

Figure 7: Scheme of chamber for TC&TD measurements at reservoir condition. 1,7,8 - pore, axial and confining pressure inlets respectively, 2 - electrical wires, 3 –elastic sleeve, 4 – container, 5 – external heater, 6 – plunger for axial pressure, 9 – spacers, 10 - heat screen, 11 - thermal insulation.

The slabbed sample halves are placed into an elastic sleeve which is compressed with outer pressure by a mineral oil which provides the basic lithostatic (confining) pressure. Pressure components are adjusted by a hydraulic compressor. The external heater is placed outside of the jacket to heat the rock sample up to in-situ temperature.

Metrological testing of the instrument has been performed on a set of six reference samples (glasses studied in industrial thermal physics) and a single quartz crystal with TC and TD values within respective ranges of 0.71–10.7 $Wm^{-1}K^{-1}$ and (0.557–5.42) 10^{-6} m^2/s at a simultaneous influence of elevated temperature and pressure. A single natural quartz crystal has also been used as a reference for anisotropy of thermal conductivity and thermal diffusivity. It is known, from the previous study of single quartz crystals of different natural types, that the thermal properties of single quartz crystals are stable and independent of their source of origin (Beck, 1977, 1987; Popov *et al.*, 1999).

Thermal conductivity of the single quartz crystal was measured with the new apparatus with the line sources oriented in two directions relative to the principal optical axes (C and A, B) of the crystal. The quartz crystal has hexagonal singony, therefore when the line source is oriented along the principal crystallographic axis C, the thermal conductivity tensor components λ_A and λ_B ($\lambda_A = \lambda_B = \lambda_{A,B}$) are measured directly.

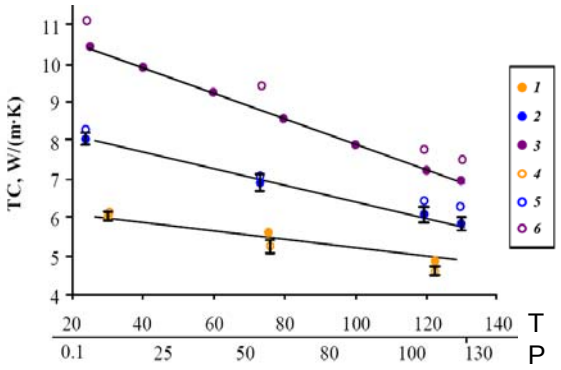

Figure 8. Comparison of TC tensor components $\lambda_{a,b}$ – (1, 4), λ_c – (3, 6) and $\lambda app=(\lambda_{a\ b}\ \lambda_c)^{1/2}$– (2, 5), measured by: 1, 2, 3—Authors and 4, 5, 6— by Beck et al., (1977). (Pressure: MPa; temperature: degC.)

When the line source is oriented perpendicular to the C axis, the apparent value of thermal conductivity λ^* measured is determined as $\lambda^* = \sqrt{\lambda_{A,B} \cdot \lambda_C}$, (Popov *et al.*, 1999). The TC tensor component λ_C can be determined from these two measurements. The measurements on a single quartz crystal allowed us to test the applicability of the instrument developed for measurements of thermal conductivity and thermal diffusivity tensor components on one rock sample. The TC and TD tensor component values measured with the new PT instrument at normal conditions correspond satisfactorily to the reference TC values (Beck, 1987; Popov *et al.*, 1997). As for TD values, they have been found to be $a_{A,B} = 2.97 \cdot 10^{-6}$ m^2/s and $a_C = 5.18 \cdot 10^{-6}$ m^2/s. From the comparison of the new and published (Beck, 1977) experimental data for elevated PT conditions (Fig. 8), one can conclude that these TC values coincide well (within both measurement errors). From testing the instrument on a single quartz crystal with simultaneous influences of elevated temperature and pressure, total accuracy plus precision value of thermal conductivity and thermal diffusivity measurements have been established to be respectively 4 and 7% (at a confidence probability rate of 0.95). Our experimental results of the sequential measurements of sandstone TC at (1) independent influence of pressure, (2) independent influence of temperature, and (3) at simultaneously acting elevated pressure and temperature, are presented in Fig. 9. From analysis of the results we can conclude that TC variations with simultaneous influences of pressure and temperature cannot be estimated from measurements with independent influences of

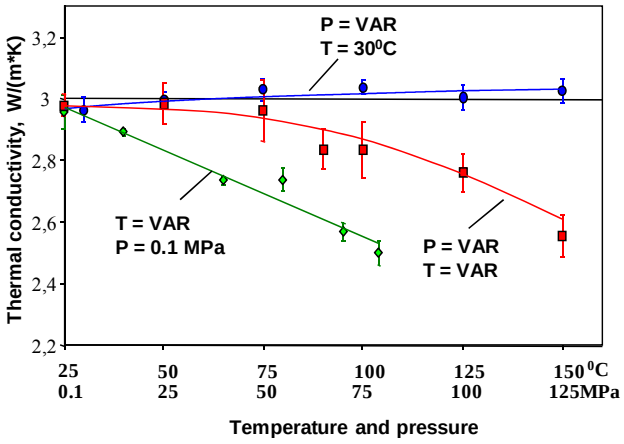

Figure 9. Experimental results of sequential measurements of sandstone TC.

elevated pressure and temperature. Therefore, an approach where the effect of the simultaneous influences of elevated pressure and temperature is estimated from TC measurements at independent influences of pressure and temperature must be used with caution.

New Technique for Formation Fluid Thermal Conductivity Measurements at Elevated Temperatures

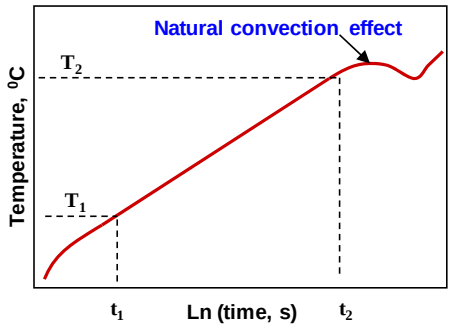

Figure 10. Typical dependence of temperature versus logarithm of time for the fluid TC measurements procedure.

A new technique for TC measurements based on the line-source theoretical model has been developed. The main advantage of the developed technique is that an operator can manually choose a time interval for experimental data processing. Thus the disturbing effect of natural fluid convection can be excluded from the measurement results (Fig. 10). For measurements of fluid TC at elevated temperatures, a needle probe is installed vertically into a high-temperature cell. Metrological testing of the developed technique has been performed. Distilled water and glycerol were used as reference fluids for testing since dependencies on TC versus temperature are well known for these fluids. It was found that the estimated precision is ± 3.5% (at a confidence of probability 0.95) and systematic deviation does not exceed 5%. The lower bound of the fluid viscosity range, where the accurate measurements can be done with the quality mentioned above, is $3 \cdot 10^{-4}$ Pa·s.

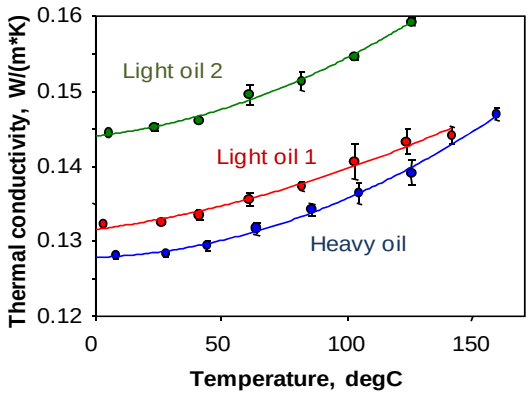

Figure 11. Thermal conductivity of the heavy oil, light oil 1, and light oil 2 versus temperature.

The TC values of three different types of oil from different oil fields were measured with the developed instrument at an elevated temperature of up to 160 degC: (a) heavy (viscous) oil, (b) light (low-viscous) oil 1, and (c) light (low-viscous) oil 2. The experimental data on TC at elevated temperatures are presented in Fig. 11. It was established that relative variations in TC versus temperature for all three oils studied can be approximated with one regression equation.

Instrument for Measurements of Linear Thermal Expansion Coefficient of Rocks

The quartz dilatometer for the measurements of the coefficient of linear thermal expansion (CLTE) of rock and mineral samples has been modified to provide the CLTE measurements on core plugs (cylinders with diameter of 30 mm and height of 30 mm).

The instrument allows us also to measure the CLTE on cubes with a side of 30 mm. It provides reliable data on CLTE anisotropy when we measure the CLTE in three cube positions. Such a measurement technique excludes the inhomogeneity influence that cannot be allowed if we study the CLTE anisotropy on three samples prepared from one rock sample along three perpendicular directions as is recommended usually. The instrument provides the CLTE measurements for every temperature interval of 20^{o}C that allows us to establish a regularity in the CLTE variations within the temperature range of 20- ^{o}C with a temperature step of 20 oC. A total relative accuracy + precision (at a confidence probability of 0.95) for every 20^{o}C interval was established from the metrological experiments to be not more than ±4%.

Metrological testing of the developed CLTE instrument has been performed on the certificated reference standards (fused quartz, silicon single crystal, cuprum, aluminum) with the CLTE values within the range of (0.5-24.6)·10^{-6} K^{-1}, that covers in general a range of rock and mineral CLTE values (2.5-18)·10^{-6} K^{-1}.

The CLTE instrument has been used for regular measurements on core collections for carbonate rocks from oil-gas fields in the West Siberia (Russia). High precision and the possibility to determine the CLTE value for every 20 ^{o}C temperature interval allowed the establishment of the CLTE vs temperature dependence within a temperature interval of 20…100^{o}C which was chosen to prevent rock sample destruction. The CLTE values were found to range over (3.48-10.8)·10^{-6} K^{-1} at 30 ^{o}C and (4.50-14.4)·10^{-6} K^{-1} at 100 ^{o}C.

CONCLUSIONS

1. Developed technique and instruments allow us to exclude many serious problems which are typical for the traditional methods and instruments for the measurements of the rock thermal properties.
2. The new experimental and theoretical base provides essential improvements in thermal property data of formations.
3. The optical scanning technology provides high-precision measurements, a high speed of operation, a contactless mode of measurement, the ability to measure directly on full size cores and core plugs without mechanical treatment with simultaneous determination of thermal conductivity, thermal diffusivity, and thermal anisotropy as well as the estimation of the inhomogeneity of rocks.
4. The optical scanning technology reveals the possibility to study correlations between thermal properties and other physical properties from measurements on the same core plugs thus reducing the disturbing influence of rock inhomogeneity and anisotropy—allowing us to establish more reliable correlations between properties overall.
5. The essential thermal inhomogeneity of rock formations discovered with the numerous optical scanning measurements demonstrates the necessity of the measurements on representative core collections with detailed core sampling along wells.

6. The new instrument for rock thermal property measurements at formation conditions allows us to determine simultaneously the thermal conductivity and diffusivity tensor components with simultaneous influences of elevated temperature and three-component pressure (pore, axial and confining pressure components).
7. The instrument developed for thermal fluid conductivity measurements can be applied for fluids with a wide range of viscosity without the disturbing influences of thermal convection in low-viscous fluids.

REFERENCES

1. Asaad, Y., 1955. "A study of the thermal conductivity of fluid bearing porous rocks". PhD Dissertation, Univ. of Calif., Berkeley, 71 p.
2. Beck A. E., Darbha D.M., and Schloessin H.H., 1977. "Lattice conductivities of single-crystal and polycrystalline materials at mantle pressure and temperatures". *Physics of the Earth and Planetary Interiors*, 17, pp. 35–53.
3. Beck A.E., 1987. "Methods for determining thermal conductivity and thermal diffusivity". *Handbook on Terrestrial Heat Flow Density Determination*. Eds. R. Haenel, L. Rybach, L. Stegena., Kluwer, and Dordrecht, pp. 87-124.
4. Brigaud, F., 1989. "Conductivite thermique et champ de temperature dans les bassins sedimentaires a partir des données de puits". Documents et Travaux, Centre Géologique et Géophysique De Montpellier, 23, 419 p.
5. Horai, K., Susaki, J., 1989. "The effect of pressure on the thermal conductivity of silicate rocks up to 12 kbar". *Physics of the Earth and Planetary Interiors*, 55, pp. 292-305.
6. Miklashevskiy D.E., Popov Yu.A., Vertogradskiy V.A., and Bayuk I.O., 2006. "Measurements of principal components of tensors of thermal conductivity and thermal diffusivity of rocks at formation thermobaric conditions". Geologiya I Razvedka (Geology and Exploration), 6, pp.38-42 (in Russian).
7. Popov Yu., Tertychnyi V., Romushkevich R., Korobkov D., and Pohl J., 2003. "Interrelations between thermal conductivity and other physical properties of rocks: experimental data". *Pure and Appl. Geophys*., 160, pp. 1137-1161.
8. Popov Yu., 1997. "Optical scanning technology for nondestructive contactless measurements of thermal conductivity and diffusivity of solid matters". Proceedings of the 4th World Conf. Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, Brussels, 1, pp.109–117.
9. Popov Yu. A., Pribnow D., Sass J., Williams C., and Burkhardt H., 1999. "Characterization of rock thermal conductivity by high-resolution optical scanning". *Geothermics*, 28, pp.253-276.
10. Schoen, J.H., 1996. Physical properties of rocks: "Fundamentals and principles of petrophysics". *Handbook of Geophysical Exploration*, Section I, Seismic exploration, 18, Redwood Books, Trowbridge, 468 p.
11. Somerton W. H., 1992. "Thermal properties and temperature-related behavior of rock/fluid systems". Amsterdam, Elsevier, 257 p.