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Thermal Properties of Formations from Core Analysis: Evolution in Measurement Methods, Equipment, and Experimental Data in Relation to Thermal EOR

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Abstract

New methods and instruments developed for measurement of rock thermal properties (thermal conductivity, thermal diffusivity, volumetric heat capacity, and coefficient of linear thermal expansion) have provided a sharp increase in the quality of experimental data for reservoirs and surrounding formations. Optical scanning technology primarily provides numerous high-precision, nondestructive, noncontact measurements of thermal conductivity and diffusivity directly on full cores, core plugs, and nonconsolidated rock samples and enables determination of thermal property tensor components and the recording of thermal property variations along cores. The instrument for simultaneous determination of thermal conductivity, diffusivity at formation temperature (up to 250 degC), and three-component pressure (pore, confining axial, and lateral) enables measurements at formation conditions to study thermal property variations during the heating of reservoirs and oil production in thermal enhanced oil recovery (EOR). The instrument for measurements of the coefficient of linear thermal expansion at temperatures up to 250 degC within every temperature interval of 20 degC provides measurements on core plugs that account for rock anisotropy. Application of the new techniques to study more than 8,000 cores from 17 Russian oil-gas and heavy oil fields provided a representative thermal property database for sedimentary rocks saturated by brine, oil, and gas, accounting for rock anisotropy and inhomogeneity as well as formation pressure and temperature. New correlations between thermal and other physical properties were established. The new experimental data demonstrated that previous information on thermal reservoir properties often needs to be significantly corrected. The new instruments provided detailed information on the spatial and temporal variations in the thermal reservoir properties during thermal EOR. Authors used this to construct detailed 4D reservoir models for estimation of reservoir thermal regime, thermal losses, and heat and mass transfer within reservoirs, enabling better design and optimization of thermal methods of EOR.

Introduction

The thermal properties of rock stipulate the thermal processes in formations. The thermal conductivity (TC), I , determines how easily heat can pass through a formation during formation heating or cooling and links the heat flow density, q , and the temperature gradient, $gradT$, in Fourier's law of heat conduction:

$$q = -I \cdot gradT .$$

The thermal conductivity, thermal diffusivity (TD), a , and volumetric heat capacity (VHC), C , are interconnected by the formula $aC = I$. The thermal diffusivity characterizes the propagation rate of the temperature front within the media during thermal transient processes. Volumetric heat capacity determines the quantity of heat energy which is necessary to heat 1 m^3 of material by 1 K. The coefficient of linear thermal expansion (CLTE) determines how much is relative linear expansion of rock at reservoir heating and connected to formation mechanical stress and wellbore stability problem.

Data on the thermal properties mentioned are important for other goals in applied and basic geophysics also: (1) interpretation of temperature logging data, (2) theoretical modeling heat and mass transfer in formations, (3) determination of heat flow density and its distribution along wells and interpretation of its vertical variations, and (4) prediction of other formation physical properties from the correlations found between thermal and other physical properties. In thermal methods of oil recovery the thermal properties are especially important because they influence economical aspects of heavy oil production.

The increasing necessity for thermal property data stimulated the development of new, effective approaches and equipment to provide more reliable and detailed information about rock thermal properties. Recently, advances in determining the thermal properties from the measurements in wells have been made through the development of temperature relaxation methods (Wilhelm 1990) and various types of logging tools (Burkhardt et al. 1990; Williams and Anderson 1990; Pribnow et al. 1993; Kukkonen et al. 2007). While valuable to specialized applications and important for interpolation of properties between widely spaced core samples collected in a well, these approaches are no substitutes for laboratory measurements on rock samples when cores and cuttings are available. In spite of the numerous instruments for the laboratory measurement of rock thermal properties developed in previous years, the following unsolved problems did not allow acquisition of representative and reliable information on the rock thermal properties, especially for reservoirs: (1) strong impact of the thermal resistance of a sample-equipment contact on the measurement results, particularly for porous and fractured rocks, (2) unsatisfactory metrological parameters (with the accuracy and precision value exceeding 7 to 8% in most cases), (3) significant influence of rock heterogeneity and anisotropy that could most often not be accounted for, (4) practically no reliable technique for thermal diffusivity measurements and simultaneous thermal conductivity and thermal diffusivity measurements on rock samples, (5) impossibility to measure thermal conductivity and thermal diffusivity tensor components simultaneously in most cases, (6) impossibility of providing nondestructive measurements on full cores and core plugs saturated with brine, oil, and gas, (7) serious problems with the measurements on nonconsolidated rocks, (8) absence of instruments for the simultaneous measurements of thermal conductivity and thermal diffusivity tensor components under concurrent influence of formation temperature up to 200 to 250 degC and elevated pressure, (9) difficulties with the measurements of coefficient of linear thermal expansion at elevated temperatures (up to 250 degC) with measurements within very narrow temperature intervals (15 to 25 degC) that did not allow determination of a temperature dependence of the parameter.

Results

Highly effective methods and a set of new instruments for thermal property measurements have been developed recently to remove the disadvantages mentioned and provide qualitative new possibilities to obtain numerous reliable data on the thermal properties from measurements on cores and nonconsolidated rocks. These new methods and instruments for measurement of rock thermal properties has provided a sharp increase in the quality of experimental data on thermal conductivity, thermal diffusivity, volumetric heat capacity, and the coefficient of linear thermal expansion of reservoirs and surrounding formations. These methods and instruments have been introduced for oilfield studies.

OS Technique for Multiple Nondestructive Noncontact Measurements on Cores at Normal Conditions

The optical scanning (OS) method and instruments have been developed for noncontact measurements of thermal conductivity and thermal diffusivity of rocks and minerals. The OS principle is a relatively new approach to thermophysical measurements. We conducted a series of theoretical and experimental investigations to evaluate its potential, and prototype measuring units were constructed (Popov 1997; Popov et al. 1999). The theoretical model of the OS method is based on scanning a sample surface with three temperature sensors (1, 2, and 3) in combination with a focused, mobile, and continuously operated constant heat source (**Fig. 1**). The heat source and sensors move with the same speed, v , relative to the sample and at a constant distance to each other. Sensor 1 displays the value of unheated sample surface temperature, θ_1 , to take initial temperatures of the solids into account. Sensors 2 and 3 display the values of the rise of corresponding maximum temperatures, θ_2 , and θ_3 , along the heating line behind the source.

Quasi-stationary excessive temperature rise, $\theta_2 - \theta_1$, in a moving coordinate system is determined by the relationship

$$Q_2 - Q_1 = \frac{Q}{2p \cdot x \cdot I}, \quad (1)$$

where Q is the source power and x is the distance between the source and Sensor 2.

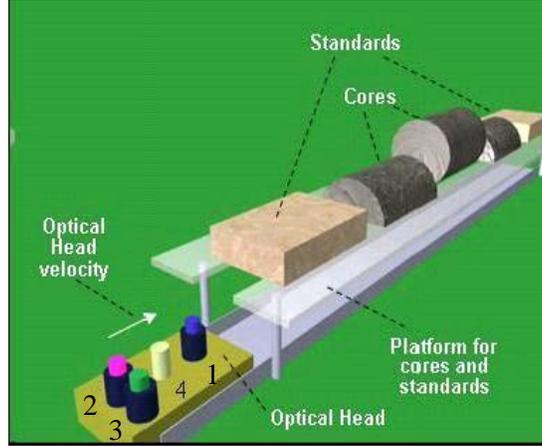


Fig. 1. Schematic of a field version of the OS instrument.

If the samples under study and two reference standards with known conductivities λ_{R1} and λ_{R2} and thermal diffusivities correspondingly a_1 and a_2 are aligned along the scanning direction, the thermal conductivity of each sample can be determined from the λ_R value and the ratio of $(\Theta_2 - \Theta_1)$ to $(\Theta_{R2} - \Theta_{R1})$ (for any reference standard R_1 or R_2) or, in actual application, from the ratio of electric signals $(U_2 - U_1)$ to $(U_{R2} - U_{R1})$, which are proportional to $(\Theta_2 - \Theta_1)$ to $(\Theta_{R2} - \Theta_{R1})$ values:

$$I = I_R(\Theta_{R2} - \Theta_{R1}) \times (\Theta_2 - \Theta_1)^{-1} = I_R(U_{R2} - U_{R1}) \times (U_2 - U_1)^{-1}. \quad (2)$$

For an anisotropic solid, the maximum temperature rise for Sensor 2 is determined by the relationship (Popov et al. 1999)

$$\Theta = \frac{Q}{2p \cdot x \cdot \sqrt{I_A \cdot I_B \cdot \cos^2(g') + I_A \cdot I_C \cdot \cos^2(b') + I_B \cdot I_C \cdot \cos^2(a')}}}, \quad (3)$$

where Θ is sample excessive temperature, a' , b' , and g' are angles between the A, B, and C principal axes of thermal conductivity and the scanning line.

After scanning along three noncollinear and noncoplanar directions that are located on two nonparallel planes, Eqs. 2 and 3 provide a means of determining the principal values of thermal conductivity from a set of three equations with three unknowns. For a sample with two-dimensional anisotropy, the principal values of conductivity can be determined from two noncollinear scans on one face, if this face is not parallel to the foliation.

The thermal diffusivity value of the samples under study can be determined using the following equation (Popov 1997):

$$a = \frac{a_{R1} \cdot \ln\left(\frac{I_{R1} \cdot \Theta_{R1}}{I_{R2} \cdot \Theta_{R2}}\right)}{\ln\left(\frac{I_{R1} \cdot \Theta_{R1}}{I_{R2} \cdot \Theta_{R2}}\right) + \frac{a_{R2} - a_{R1}}{a_{R2}} \cdot \ln\left(\frac{I \cdot \Theta}{I_{R1} \cdot \Theta_{R1}}\right)} \quad (4)$$

OS allowed us to record the variations of thermal conductivity and diffusivity along the inhomogeneous sample and determine thermal conductivity and diffusivity tensor components for three-dimensional anisotropy. The other merits of OS include (1) high

precision (1.5%) and accuracy (1.5% for a confidence probability of 0.95) of thermal conductivity measurements within the range of 0.1 to 70.0 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, (2) high precision (2%) and accuracy (2%) of thermal diffusivity measurements within the range of (0.1 to 5.0) $\cdot 10^{-6}$ $\text{m}^2/\text{s}\cdot\text{K}$, (3) the ability to sample deeply using a slow scanning rate, (4) freedom from constraints for sample size (1 to 70 cm in sample length) and shape and quality of mechanical treatment of the sample surface, (5) a contactless mode of measurements, (6) short time of measurement (10 to 30 s) for every sample, (7) the ability to measure on a flat or cylindrical sample surface, and (8) the possibility to measure full cores and core plugs.

Two versions of OS instruments have been elaborated: (1) the laser version for the measurements on core plugs and small pieces of rocks (from $1 \times 1 \times 1$ cm and larger), and (2) the field version for numerous measurements on full cores in laboratory and core storages (**Fig. 2**). Both versions provide simultaneous measurement of thermal diffusivity as well as conductivity. The laser (or focused electric bulb) heat source and infrared radiometers for measurements of initial and maximum sample temperatures are placed on a platform and move at a constant speed relative to samples and reference standards. Measurements are carried out on dry or fluid-saturated samples. In the case of cylindrical samples, scans are oriented along the core axis and the bottom face of the core. Surface roughness of up to 1.0 mm is allowable. In general, it is not necessary to polish a sample surface. If the scanned surface is too rough, systematic errors can be corrected for based on results from reference standards with a similarly rough surface. The working surface of the sample is covered with an optical coating (25 to 40 μm thick) to minimize the influence of varying optical reflection coefficients. Sample sizes in this study varied from 1 to 70 cm in length, 2 to 30 cm in width, and 2 cm or more in thickness.



Fig. 2. OS instrument for rock thermal property measurements on full size cores.

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 by a change in measurement regime including the speed of scanning and the distance between the heated spot and the area of temperature recording. The layer thickness also depends on the thermal properties of the sample and may reach 2 to 3 cm or more for samples with thermal conductivity exceeding 6 to 7 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$.

The signal-processing algorithm yields the effective conductivity of two perpendicular directions for an inhomogeneous layered sample. The mean value of excessive temperature along the scanning profile is used in Eq. 2 to determine thermal conductivity in the orientation coincident with the scanning direction, and the thermal conductivity 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 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and thicknesses varying from 1 to 15 mm have shown that this determination of effective thermal conductivity does not differ significantly from the calculated thermal conductivity of layered samples. Local thermal conductivities and thermal diffusivities can be determined for grain scales as small as 7 to 10 mm.

After the scanning is completed, the following information is available for each sample:

- Thermal conductivity and thermal diffusivity profiles along a single scanning line
- Effective thermal conductivity and thermal diffusivity of each sample for two mutually perpendicular directions and related macroanisotropy factor
- Thermal inhomogeneity factor (defined as maximum difference in conductivity along the scanning line divided by effective thermal conductivity), and the RMS deviation of local thermal conductivity values along each scanning line

At present, the measurable range of conductivity is 0.1 to 70 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. The rate of measurements is between 50 and 70 measurements per hour.

The new OS method and instruments described have been used to perform measurements on collections of more than 200 rock-forming minerals (single crystals and aggregates) to correct and extend the data on thermal properties of minerals and their anisotropy and provide more reliable information for interpretation of rock thermal property variations. The new technologies have provided measurements on cores from deep wells sampled at intervals of 1 to 2 m. Significant vertical variations in rock thermal properties were established in every case (the example of a thermal property log obtained on cores from a sandstone formation is given in **Fig. 3**). Our results from measurements on more than 80 000 cores from wells (including the scientific deep) drilled in different geological structures including sedimentary basins have shown that rock thermal conductivity correlates well with reservoir properties and is essentially anisotropic in most cases but varies in rock formations significantly (often by several times) even within cores and short depth intervals (several meters) in formations.

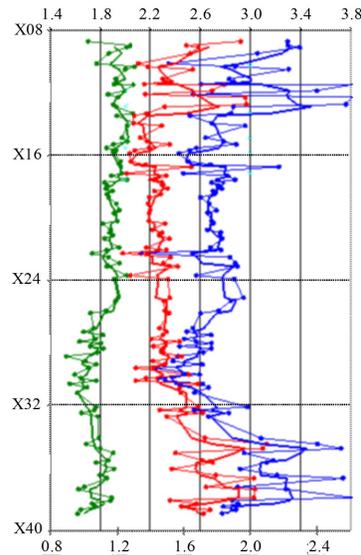


Fig. 3. Thermal conductivity (blue), thermal diffusivity (red), and volumetric heat capacity (green) logs from the OS measurements on cores from a heavy oil quartz sandstone formation. Points represent original measurement data, thick lines correspond to the data from the filtering (box with 4 points), and vertical straight lines show mean values of the thermal properties within different depth intervals restricted by statistical boundaries found.

Vast amounts of new information about correlations between thermal and other physical properties (porosity, permeability, sonic velocity, electric resistivity) have been obtained from the measurements on more than 5000 core plugs of different sedimentary rocks as a result of the possibility to measure many different physical properties on the same sample that reduced or excluded the rock inhomogeneity influence. Close correlations between thermal conductivity and porosity, Φ , of reservoirs are very stable, and the correlations between permeability and relative change, $\delta\lambda = \lambda_{\text{dry}}/\lambda_{\text{sat}}$, in thermal conductivity after water-saturation of rock samples (λ_{dry} is thermal conductivity of dry rock samples and λ_{sat} is thermal conductivity of water-saturated rock samples) were established also (**Fig. 4**).

Measurements of Rock and Mineral Thermal Properties at Formation Pressure and Temperature

An instrument for measurement of rock and mineral thermal conductivity and thermal diffusivity with simultaneous influence of temperature (up to 250C), and pore and two components of lithostatic pressures (up to 200 MPa) has been developed. The measuring pressure-temperature chamber of the instrument is shown in **Fig. 5**. A new approach in the line-source method has provided simultaneous measurements of TC and TD tensor components within one measurement cycle (**Fig. 6**).

Comprehensive metrological study of instruments designed for TC and TD measurements at simultaneous influence of elevated pressure, P , and temperature, T , at pressure up to 250 MPa and temperature to 250 degC is very complicated; at present there are no reliable references and organizations for industry standards could not help with the problem. In this study the instrument metrological testing was performed on a set of six reference samples (glasses studied in industrial thermal physics) and a quartz single crystal with TC and TD values within ranges of respectively 0.71 to 10.7 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and $(0.557 \text{ to } 5.42)\cdot 10^{-6} \text{ m}^2/\text{s}$ at concurrent influence of elevated temperature and pressure. A natural quartz single crystal was used also as a reference of anisotropy of thermal conductivity and thermal diffusivity. Previous studies of quartz single crystals of different natural types have established that their thermal properties are stable independently ofn their origination (Beck et al. 1977; Beck 1987; Popov et al.

1987, 1999). The quartz TC values used came from the consistent experimental data at room temperature determined by Beck (1987) ($6.07 \pm 0.10 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for the A and B axes and $10.5 \pm 0.1 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for C axis) and Popov et al. (1987, 1999) ($6.05 \pm 0.05 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for A and B axes and $10.7 \pm 0.1 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ for C axis).

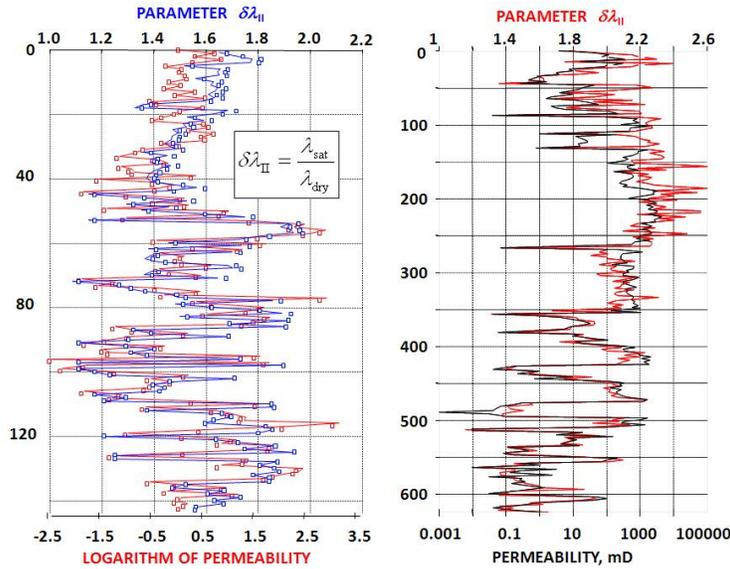


Fig. 4. Logs of parameter $dl = l_{dry}/l_{sat}$ (blue line) and logarithm of permeability (red line) (left panel) and thermal conductivity l_{dry} and solidity $1 - F$ (right panel). Accuracy and precision of thermal conductivity measurements are 1.5% each (confidence probability of 0.95).

Thermal conductivity of the quartz single 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. When the line source is oriented perpendicularly to the C axis the apparent value of thermal conductivity, λ^* , measured is determined as $I^* = \sqrt{I_{a,b} \cdot I_c}$ (Popov et al. 1999). The TC tensor component, λ , can be determined from these two measurements. The measurements on a quartz single crystal enabled testing of the applicability of the instrument developed for measurements of thermal conductivity and thermal diffusivity tensor components on one rock sample. Values for the TC and TD tensor components measured with the new instrument at normal conditions simultaneously with two line sources, oriented perpendicularly each to other, were found to be $I_{a,b} = 5.98 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ in the direction perpendicular to the main optical axis C and $I_c = 10.5 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ in the parallel direction, which corresponds satisfactorily to the TC values established earlier and previously mentioned (Beck 1987; Popov et al. 1987). TD values were equal to $a_{a,b} = 2.97 \cdot 10^{-6} \text{ m}^2/\text{s}$ and $a_c = 5.18 \cdot 10^{-6} \text{ m}^2/\text{s}$.

Results from comparing simultaneous measurements of TC tensor components at normal thermodynamical conditions and at elevated temperatures (up to 130 degC) and confining pressures (up to 130 MPa) with experimental data reported by Beck et al. (1977) are presented in **Fig. 7**. From the comparison of the new and published (Beck 1977) experimental data for elevated pressure and temperature conditions one can conclude that these TC values coincide well (within both measurement errors). The metrological study described demonstrates that the reliability of the new instrument designed is not inferior to that of analogical instruments described in literature in respect in respect to accuracy and completeness of metrological study. From tests on a quartz single crystal with simultaneous influence of elevated temperature and pressure, the total accuracy and precision of values from the thermal conductivity and thermal diffusivity measurements have been established as 4 and 7% (a confidence probability of 0.95).

Behavior of TC and TD tensor components of quartz, calcite, and potassium feldspar single crystals have been registered at simultaneous influence of temperature (up to 220 degC) and confining pressure (up to 200 MPa). Analysis of experimental data and comparison with literature data have revealed that the average difference in their values (1) does not exceed 5% for quartz, and (2) increases systematically up to 12% with the pressure and temperature increase for calcite and potassium feldspar single crystals.

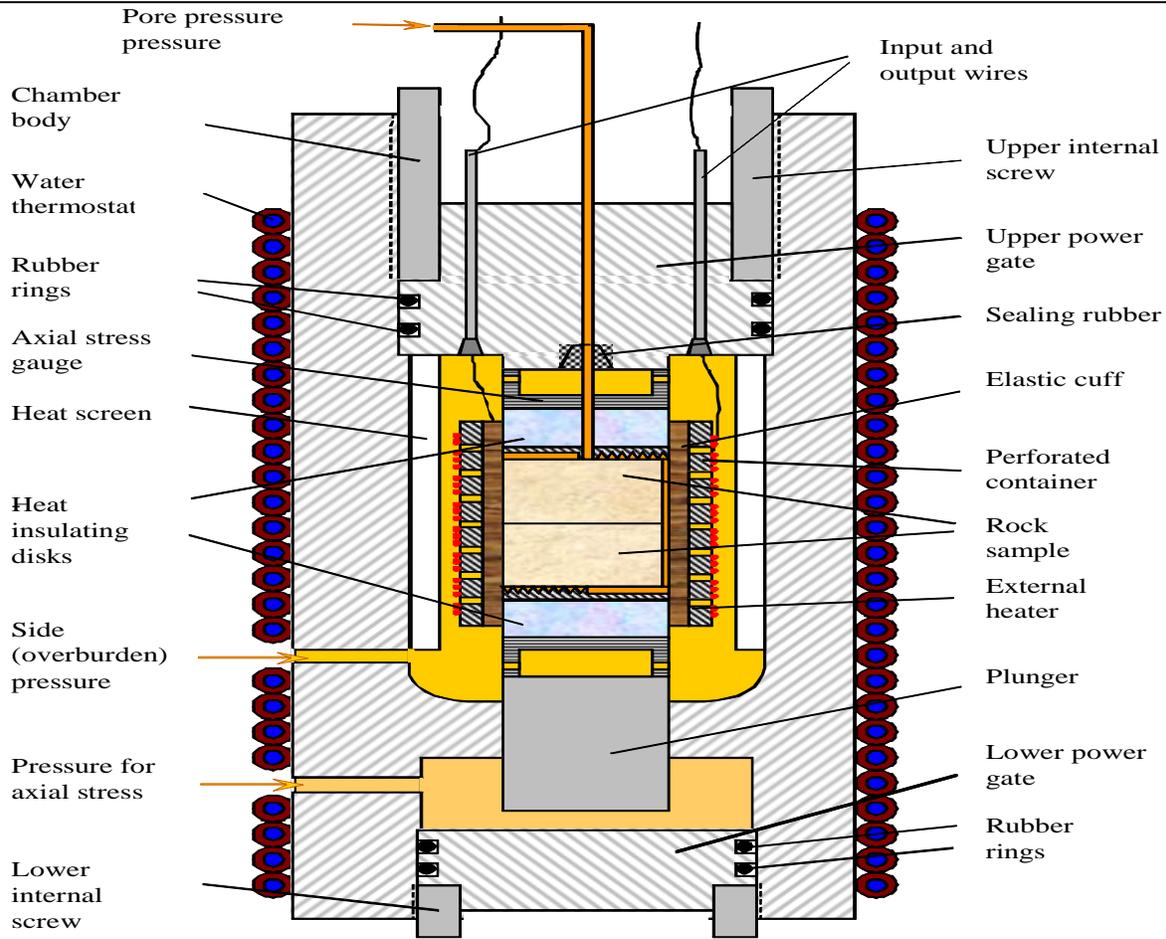


Fig. 5. Schematic of chamber for thermal conductivity measurements at elevated temperature and pressure (pore pressure and two components of confining pressure).

According to the measurement results for sedimentary rocks at elevated temperature (25 to 220 degC) and equal vertical and horizontal components of lithostatic pressure (up to 200 MPa) and pore pressure (up to 80 MPa), the thermal conductivity and thermal diffusivity decrease at pressure of 180 MPa and temperature of 120 degC by -9(-46)% and -14, . . . , -64% respectively.

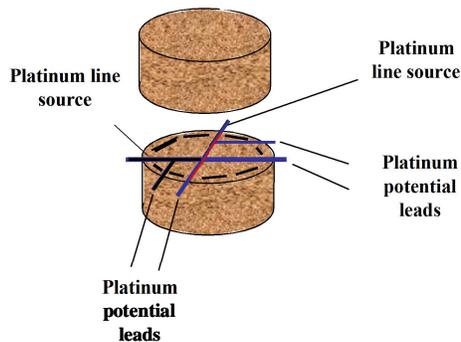


Fig. 6 Measurement cell elaborated for simultaneous measurements of TC and TD tensor components at elevated pressure and temperature conditions.

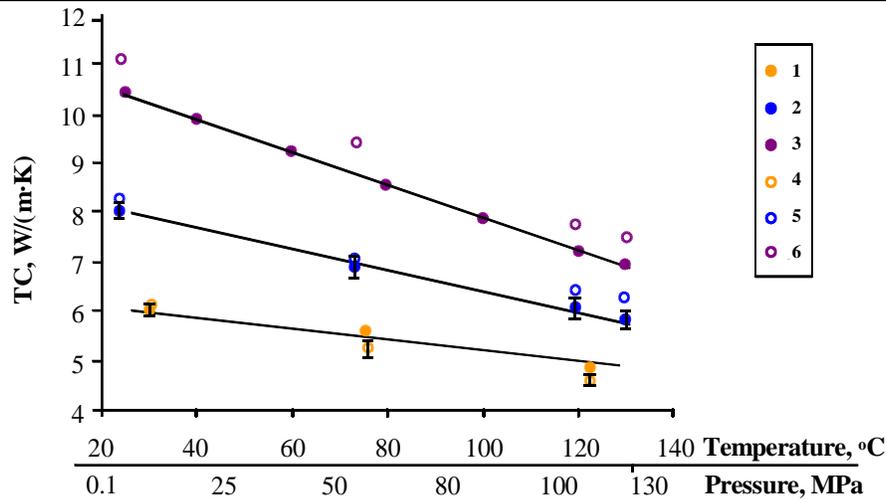


Fig. 7. Comparison of TC tensor components $\lambda_{a,b}$ – (1, 4), λ_c – (3, 6) and $I_{app} = \sqrt{I_{a,b} I_c}$ – (2, 5), measured by 1, 2, 3 – RSGPU and 4, 5, 6 – by Beck et al. (1977).

New Technique for Fluid Thermal Conductivity Measurements at Elevated Temperatures

A new technique for thermal conductivity measurements based on the line-source theoretical model has been developed. The measuring needle probe consists of a platinum heater and potential taps for temperature recording. The technique's main advantage is that an operator can manually choose the time interval for experimental data processing from an observation of signal temporal variations (Fig. 8). Thus the disturbing effect of fluid natural convection can be excluded from the measurement results.

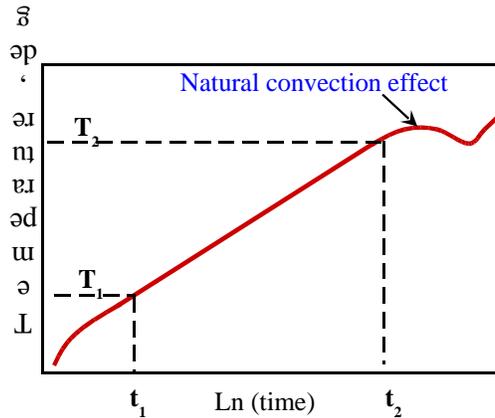


Fig. 8. Temperature versus time plot demonstrating thermal convection effect which can disturb the measurement results.

For measurements of fluid TC at elevated temperature the needle probe is installed vertically into a high-temperature cell to reduce the natural convection effect (compared to that in a horizontal position) and placed into a programmable high-temperature furnace.

Metrological testing of the developed technique has been performed. The distilled water and glycerin were used as reference fluids for testing because the dependencies of thermal conductivity versus temperature are well known for these fluids (Vargaftik 1990). The metrological testing results and the reference data are given in Figs. 9 and 10 for a temperature range of 0 to 160 degC.

Estimated precision is $\pm 3.5\%$, a confidence of probability of 0.95, and systematic deviation does not exceed 5%. It was established from the metrological testing that a lower bound of the fluid viscosity range for the measurement accuracy mentioned is $3 \cdot 10^{-4}$ Pa·s.

Instrument for Measurements of Linear Thermal Expansion Coefficient of Rocks

The quartz dilatometer for measurement of CLTE of rock and mineral samples has been elaborated. The instrument provides CLTE measurements on crystals of rock-forming minerals and core plugs (cylinders with diameter of 30 mm and height of 30 mm) used in petrophysics studies to derive many physical properties. CLTE measurements can be performed on cubes with a side measurement of 30 mm. The instrument provides reliable data on CLTE anisotropy if CLTE is measured in three cube positions. This measurement technique excludes the inhomogeneity influence that is typical for conventional approaches when CLTE anisotropy is studied on three different samples prepared from one rock sample along three perpendicular directions.

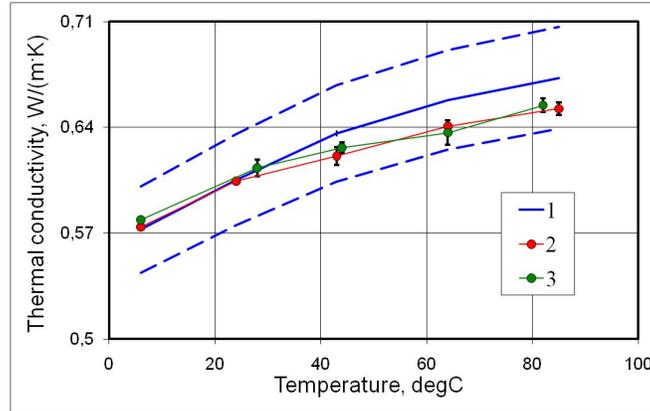


Fig. 9. Comparison of measured thermal conductivity of water with the reference data: 1 represents the reference data; 2, the first cycle of measurements; 3, the second cycle of measurements. Bars on the experimental data are the RMS values. Dashed blue lines are the $\pm 5\%$ values of reference data.

Numerical modeling of the temperature field within a sample volume during its heating and cooling under the CLTE measurements allowed us to estimate temperature gradients within the sample depending on sample dimensions and thermal properties and rate of heating and cooling. This resulted in better measurement quality. To test the numerical model results, the experiments were performed when thermocouples were placed into the sample and on its surface. It was established from the theoretical and experimental results that rate of sample cooling and heating should not be larger than 1 K/min and the temperature gradient within the sample should not be larger than 0.5 K/cm.

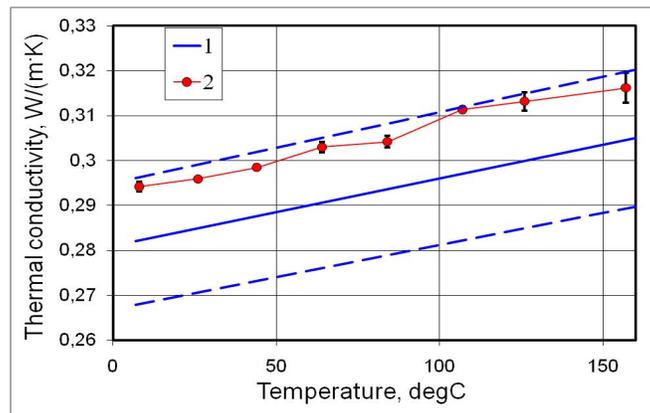


Fig. 10. Comparison of measured thermal conductivity of glycerin with the reference data: 1 represents the reference data and 2, the experimental data. Bars on the experimental data are the RMS values. Dashed blue lines are the $\pm 5\%$ values of reference data.

The instrument provides CLTE measurements for every temperature interval of 20 degC, which allowed us to establish a regularity in the CLTE variations within the temperature range of 20 to 250 degC with a temperature step of 20 degC. A total relative accuracy and precision (at a confidence probability of 0.95) for every 20 degC interval was established from the metrological experiments to be not more than $\pm 4\%$.

Metrological testing of the CLTE instrument developed has been performed on the certificated reference standards (fused quartz, silicon single crystal, cuprum, aluminium) with CLTE values within the range of $(0.5 \text{ to } 24.6) \cdot 10^{-6} \text{ K}^{-1}$, which covers in general a

range of rock and mineral CLTE values of $(2.5 \text{ to } 18) \cdot 10^{-6} \text{ K}^{-1}$. The measurements on a quartz crystal have shown that the discrepancy is observed between previous and experimental data on the quartz CLTE. The current data obtained from the new instrument application exceeded by 20% the previous data (Clark 1966; Raz et al. 2002).

The CLTE instrument has been used for regular measurements on core collections for carbonate rocks from oil-gas fields in West Siberia (Russia) and quartz sandstone from a heavy oil field in the European part of Russia. A high precision and possibility to determine the CLTE value for every 20 degC temperature interval allowed us to establish the CLTE versus temperature dependence within a temperature interval of 20 to 100 degC, which was chosen to prevent rock sample destruction.

The CLTE values for carbonates ranged from $(3.48 \text{ to } 10.8) \cdot 10^{-6} \text{ K}^{-1}$ at 30 degC and $(4.50 \text{ to } 14.4) \cdot 10^{-6} \text{ K}^{-1}$ at 100 degC; for quartz sandstones they ranged from $(7.3 \text{ to } 11.5) \cdot 10^{-6} \text{ K}^{-1}$ at 30 degC and $(9.6 \text{ to } 13.2) \cdot 10^{-6} \text{ K}^{-1}$ at 100 degC. The new technique presents qualitative new possibilities for research and industrial goals. The new approaches have been used to measure reservoir thermal properties on 502 cores (quartz sandstone) from a heavy oil field (the European part of Russia). For the laboratory experiments, cores were saturated with different fluids (brine, heavy oil, and model of steam) to model transformations in pore fluids during the thermal EOR. Relevant temperature variations during reservoir heating were accounted for.

Modification of methods and instruments for thermal property measurements on nonconsolidated rock samples

A special cell for nonconsolidated rock samples has been developed to study thermal properties with the OS technique. The cell has a rectangular shape with dimensions $110 \times 65 \times 65 \text{ mm}$ and centrally placed cut on the bottom of the cell. The cut is covered with special thin synthetic film. Standard samples used with the OS technique are covered with the same film. During the measurement procedure every nonconsolidated sample is compressed with pressure from 1 to 1.5 bar.

Metrological testing of the modified method for rock samples (sands) saturated with gas, oil, and brine has been performed. Results established the precision of TC measurements at $\pm 3\%$; for TD precision, $\pm 5\%$; and for VHC, $\pm 6\%$.

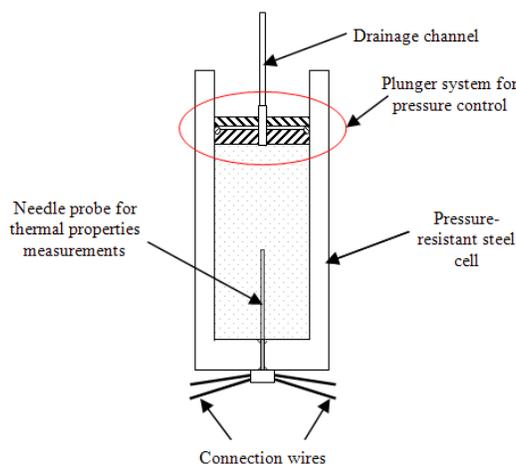


Fig. 11. Schematic of the measuring cell for nonconsolidated rock samples.

The experimental setup for thermal property measurements under formation conditions described has been modified to perform thermal properties measurements on nonconsolidated rock samples (i.e., sands) at reservoir pressure and temperatures in the range 5 to 250 degC. Modification of the setup allows measurements on nonconsolidated rock samples in the dry state and saturated with different formation fluid (brine or oil). Metrological testing of the setup has been performed. Estimated precision is $\pm 3.5\%$, a confidence probability 0.95, and the systematic deviation does not exceed 5%.

Application of technique to thermal EOR

Application of these new methods and instruments to studies of more than 8000 cores from wells drilled in 15 Russian oil-gas fields has provided a rock thermal property database that accounts for rock anisotropy and inhomogeneity as well as formation pressure and temperature. New correlations between thermal and other physical properties have been established (Popov et al. 2003, 2004). The new experimental data have demonstrated that some previously published information on thermal reservoir properties may need significant corrections.

The new technique allowed us to establish the spatial and temporal variations in the thermal reservoir properties during thermal EOR to construct detailed 4D thermal models of reservoirs for estimation of reservoir thermal regime, thermal losses, and heat and mass transfer to better design and optimize thermal methods of EOR. The reservoir thermal properties were measured with the instruments described previously on more than 560 cores (consolidated quartz sandstones and nonconsolidated polymictic sandstones) from two heavy oil fields in Russia where thermal EOR methods are in use. For the laboratory experiments, cores were saturated with different fluids (brine, heavy oil, and air as thermal physical model of steam) to model transformations in pore fluids during the thermal EOR. Relevant temperature variations during reservoir heating were accounted for. Porosity, permeability, acoustic velocities, and coefficient of linear thermal expansion were also measured for consolidated rocks, and porosity was measured for nonconsolidated rocks.

The measurements with OS technology on full-size cores, core plugs, and nonconsolidated rock samples provided representative information on spatial TC, TD, and VHC variations within reservoirs and surrounding formations. The instrument for simultaneous determination of TC and TD at formation temperature (up to 250 degC) and three-component pressure (pore, confining axial, and lateral) was used to determine thermal properties at formation conditions with temperature up to 250 degC, with a possibility of simultaneous measurements of TC and TD tensor components for the study of variations in thermal properties during the heating of reservoirs and oil production in thermal EOR. The instrument for CLTE measurements, at temperatures of up to 250 degC within every temperature interval of 20 degC, provided measurements on core plugs that account for rock anisotropy.

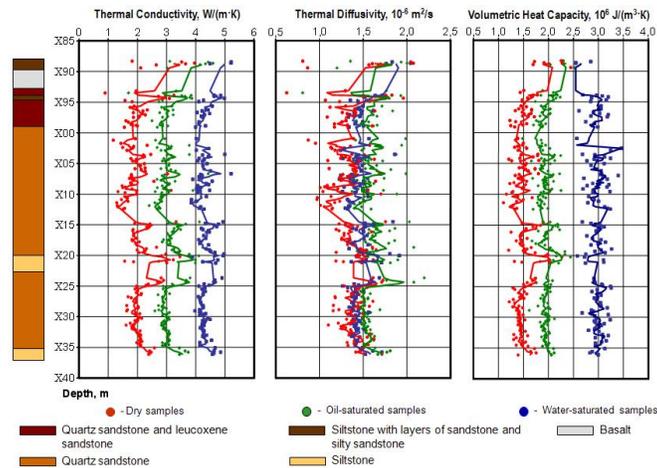


Fig. 12. Spatial variations of thermal properties depending on lithology and saturation type.

Significant spatial variations in reservoir thermal properties were established (see Fig. 3 for example). Changing the fluids in pores causes essential changes in reservoir thermal properties also (**Fig. 12**). Reservoir heating from 5 to 250 degC results in average decreases of 47% in thermal conductivity and 68% in thermal diffusivity for quartz sandstones. Average decreases for polymictic sandstones were 25.3% in thermal conductivity and 51.5% in thermal diffusivity with temperature change of from 5 to 250 degC. In total, changes in reservoir thermal properties caused by their spatial and temporal variations ranged from 0.8 to 5.2 $\text{Wm}^{-1}\text{K}^{-1}$ for thermal conductivity and $(0.6\text{-}3.0)\cdot 10^{-6} \text{ m}^2/\text{s}$ for thermal diffusivity of the quartz sandstone reservoir, and from 0.30 to 0.71 $\text{Wm}^{-1}\text{K}^{-1}$ for thermal conductivity and $0.12\text{-}0.48\cdot 10^{-6} \text{ m}^2/\text{s}$ for thermal diffusivity of the polymictic sandstone reservoir. This information is important for 4D modeling of reservoir thermal and mass transfer regime during the reservoir preheating and oil production to provide maximal EOR efficiency for specific conditions.

Changing the fluid in the pores causes essential changes in reservoir thermal properties also. Reservoir heating of up to 200 degC results in average decreases in thermal conductivity of 35% and in thermal diffusivity of 48%. In total, ranges of the reservoir thermal properties caused by their spatial and temporal variations were 0.8 to 5.2 $\text{Wm}^{-1}\text{K}^{-1}$ for thermal conductivity and $(0.6\text{-}3.0)\cdot 10^{-6} \text{ m}^2/\text{s}$ for thermal diffusivity.

For the quartz sandstone heavy oil field, the new data on reservoir thermal properties showed essentially larger values than previous results: for the reservoir approximately 56 and 51% for thermal conductivity and thermal diffusivity, respectively, and for the surrounding formation rock, 76 and 75%, respectively. We believe the differences in data can be explained by significant shortcomings in the approaches of previous experiments.

As is shown in Pimenov et al. (2009), uncertainties in reservoir properties can result essential uncertainties in predictions of heavy oil production.

The CLTE values measured on oil-saturated quartz sandstone core plugs from the heavy oil field in the European part of Russia ranged from $(10.1 \text{ to } 11.6) \cdot 10^{-6} \text{ K}^{-1}$ at 30 degC and from $(11.7 \text{ to } 13.0) \cdot 10^{-6} \text{ K}^{-1}$ at 100 degC.

Important correlations were also established between measurements of thermal and other physical properties. For the 68 quartz sandstone rock samples studied, the correlations between rock thermal conductivity and elastic velocities can be described by the following equations, if the ranges fall within 1000 to 4000 m/s for elastic compressional acoustic wave, v_p , and 1 to 5 W/(m·K) for the thermal conductivity, I :

- Air (steam) in pores $-\lambda = 0,9602 \cdot e^{0,0004v_p}$, correlation coefficient $R = 0.85$
- Brine in pores $-\lambda = 2,752 \cdot e^{0,0001v_p}$, $R = 0.71$
- Heavy oil in pores $-\lambda = 1,1272 \cdot e^{0,0003v_p}$, $R = 0.92$
- Light oil in pores $-\lambda = 1,7273 \cdot e^{0,0002v_p}$, $R = 0.83$

The established regression equations are important when the seismic monitoring is used to control the reservoir regime during the reservoir preheating and heavy oil production.

Conclusions

- 1) The OS technology provides high-precision measurements, high-speed operation, contactless mode of measurement, ability to perform measurements directly on full cores and core plugs without mechanical treatment and with simultaneous determination of thermal conductivity and thermal diffusivity, thermal anisotropy, and estimation of inhomogeneity of rocks.
- 2) Application of the OS technology reveals a possibility to study correlations of thermal properties with other physical properties from measurements on the same core plugs. Correlations reduce uncertainty caused by rock inhomogeneity and anisotropy and allow establishment of more reliable correlations between the properties.
- 3) Essential thermal inhomogeneity of rock formations discovered from the numerous OS measurements demonstrates the need for measurements on representative core collections with detailed core sampling along wells.
- 4) The new instrument for the rock thermal property measurements at formation conditions allows simultaneous determination of thermal conductivity and diffusivity tensor components under concurrent influences of elevated temperature and three-component pressure (pore, axial, confining) components.
- 5) The instrument developed for fluid thermal conductivity measurements enables measurements for a wide range of viscosities without impact of thermal convection in low-viscosity fluids.
- 6) The instrument developed for the coefficient of linear thermal expansion provides measurements of the coefficient tensor components on one sample within the temperature range of 20 to 250 degC with a temperature step of 20 degC.
- 7) Application of the methods and instruments developed to study the thermal properties of rocks from heavy oil fields provides the information necessary for optimization of thermal EOR methods.

Nomenclature

a	= thermal diffusivity, m^2/s
C	= volumetric heat capacity, $J/(m^3 \cdot K)$
$gradT$	= temperature gradient, K
q	= heat flow density, W/m^2
Q	= power, W
U	= voltage, V
v	= acoustic velocity, m/s

λ = thermal conductivity, $W/(m \cdot K)$

F = porosity, cu

θ = temperature, K

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References

- Beck, A.E. 1987. Methods for Determining Thermal Conductivity and Thermal Diffusivity. In *Handbook on Terrestrial Heat Flow Density Determination*, ed. Haenel, Rybach and Stegena, Kluwer, Dordrecht: 87–124.
- Beck, A.E., Darbha, D.M., and Schloessinm H.H. 1977. Lattice Conductivities of Single-Crystal and Polycrystalline Materials at Mantle Pressure and Temperatures. *Phys. Earth Planet. Inter.*, 17 (1977): 35–53.
- Burkhardt, H., Honarmund, H., and Pribnow, D. 1990. First Results of Thermal Conductivity Measurements with a Borehole Tool for Great Depths. In Bram. Draxler, Kessels, Zoth (eds.). *KTB Report*, 9(6a). Springer Verlag: Hannover: 245–258.
- Clark, J.S.P. 1966. *Handbook of Physical Constants*. Yale University: New Haven, Connecticut.
- Kukkonen, I., Suppala, I., Korpisalo, A. and Koshkinen, T. 2007. Drill Hole Logging Device TERO76 for Determination of Rock Thermal Properties. *Posiva 2007-01*. Geological Survey of Finland: Posiva OY: 63.
- Popov, Yu., Romushkevich, R., Bayuk, I., Korobkov, D., Mayr, S., Burkhardt, H., and Wilhelm, H. 2004. Physical Properties of Rocks from the Upper Part of the Yaxcopoil-1 Drill Hole, Chicxulub Crater. *Meteoritics & Planetary Science*, 39 (6): 799–812.
- 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: 1137–1161.
- Popov, Yu.: 1997. Optical Scanning Technology for Nondestructive Contactless Measurements of Thermal Conductivity and Diffusivity of Solid Matters. *Proc.*, 4th World Conf. Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, Brussels, 1: 109–117.
- Popov, Yu.A., Berezin, V.V., Soloviov, G.A., Romushkevitch, R.A., Korosteliyov, V.M., Kosturin, A.A., and Kulikov, A.V. 1987. Thermal Conductivity of Minerals. *Izvestiya Physics of the Solid Earth*, 23 (3): 245–253.
- Popov, Yu.A., Pribnow, D., Sass, J., Williams, C., and Burkhardt, H. 1999. Characterisation of Rock Thermal Conductivity by High-Resolution OS. *Geothermics*, 28: 253–276.
- Pimenov, V.P., Popov, Yu.A., Klemin, D.V., and Spasennykh M.Yu. 2009. Estimation of the reservoir thermal properties influence on the Steam-Assisted Gravity Drainage efficiency. *Geology and Exploration*, 4: 59-62.
- Pribnow, D., Williams, C., and Burkhardt, H. 1993. Log-Derived Estimate for Thermal Conductivity of Crystalline Rocks from the 4 km KTB. *Vorbohrung. Geophysical Research Letters*, 20: 1155–1158.
- Raz, U., Girsperger, S., and Thompson, A., 2002. *Thermal expansion, compressibility and volumetric changes of quartz obtained by single crystal dilatometry to 700°C and 3.5 kilobars (0.35 GPa)*. ETH, Eidgenössische Technische Hochschule Zürich, Department of Earth Sciences, Zürich.
- Vargaftik, N.B., Filippov, L.P., Tarzimanov, A.A., and Totskiy, E.E. 1990. *Thermal Conductivity of Fluids and Gases Handbook*. Energoatomizdat: Moscow (in Russian).
- Wilhelm, H. 1990. A New Approach to the Borehole Temperature Relaxation Method. *Geophysical Journal International*, 103: 469–481.
- Williams, C.F. and Anderson, R.N. 1990. Thermophysical Properties of the Earth's Crust: In Situ Measurements from Continental and Ocean Drilling. *Journal of Geophysical Research*, 95: 9209–9236.