NEW METHODS AND INSTRUMENTS FOR DETERMINATION OF RESERVOIR THERMAL PROPERTIES

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ABSTRACT

The new methods and instruments developed for measurements of rock thermal properties (thermal conductivity, thermal diffusivity, volumetric heat capacity, and coefficient of linear thermal expansion) provide a sharp increase in the quality of experimental data for geothermal reservoirs. Optical scanning technology firstly provides numerous high-precision, nondestructive, non-contact measurements of thermal conductivity and diffusivity directly on full cores, core plugs and non-consolidated rock samples along with determination of thermal property tensor components and the recording of thermal property variations along cores. The instrument for simultaneous determination of thermal conductivity and diffusivity at reservoir temperature (up to 250 ^{o}C), and 3-component pressure (pore, confining axial, and lateral pressures up to 200 MPa) allows the measurements at formation conditions to study thermal property variations during the heating of reservoirs and oil production in thermal enhanced oil recovery. The instrument for measurements of the coefficient of linear thermal expansion at temperatures up to 250 ^{o}C within every temperature interval of 20 ^{o}C provides measurements on core plugs accounting for rock anisotropy. One more instrument was developed for the measurements the thermal conductivity and thermal diffusivity of fluids at elevated temperatures. Application of the new technique provides a representative thermal property data for rocks saturated by brine and steam accounting for rock anisotropy and inhomogeneity as well as reservoir pressure and temperature. The new instruments provide the detailed information on the spatial and temporal variations in the reservoir thermal properties and possibility to exclude the following unsolved problems in rock thermal property measurements: (1) disturbing influence of the thermal resistance of a sample-equipment contact on the measurement results particularly for porous and fractured rocks, (2) significant influence of rock inhomogeneity and anisotropy which could not be accounted most often earlier, (3) impossibility to measure thermal conductivity and thermal diffusivity tensor components simultaneously in most cases, (4) impossibility to provide the high-precision non-destructive measurements on full cores and core plugs without mechanical treatment of cores, (5) difficulties with the measurements of differential coefficient of linear thermal expansion at elevated temperatures (up to 250°C) for the measurements within narrow temperature intervals (15-25°C). The new experimental data obtained from application of new technique on rock samples from different formations demonstrate that previous information on thermal reservoir properties often needs to be significantly corrected.

Analysis demonstrates that existing theoretical models, especially applied in the commercial simulators for thermo-hydrodynamical modeling, can not provide the reliable thermal property data prediction from other reservoir properties. The new theoretical models of effective thermal conductivity of heterogeneous medium, based on the effective medium theory, were developed to improve the quality of the rock thermal conductivity prediction.

INTRODUCTION

Data on the thermal properties of rocks such as thermal conductivity, thermal diffusivity, volumetric heat capacity are necessary for many aspects of exploration and exploitation of geothermal fields. Data on the coefficient of linear thermal expansion are required for formation stress estimation. Necessity in accurate data on the reservoir thermal property stimulate the development of new effective approaches and equipment to provide more reliable and detailed information about rock's thermal properties of reservoirs and surrounding rocks.

Recently, advances in determining the thermal properties from the measurements in wells have been made through the development thermal relaxation methods (Wilhelm, 1990), and various types of logging tools (Williams and Anderson, 1990; Burkhardt et al., 1990; Pribnow et al., 1993; Kukkonen et al., 2007). Nevertheless, these approaches are no substitutes for laboratory measurements on rock samples when cores and cuttings are available.

In spite of numerous instruments for the laboratory measurements of rock thermal properties have been developed during many previous years, the following unsolved problems do not allow to obtain representative and reliable information on the rock thermal properties especially for reservoirs: (1) disturbing influence of the thermal resistance of a sample-equipment contact on the measurement results particularly for porous and fractured rocks, (2) not

satisfactory metrological parameters (with the accuracy + precision value more than 8-10% in most cases), (3) significant influence of rock inhomogeneity and anisotropy which could not be accounted most often, (4) impossibility to measure thermal conductivity and thermal diffusivity tensor components simultaneously in most cases, (5) impossibility to provide the non-destructive measurements on full cores and core plugs, (6) absence of instruments for the simultaneous measurements of thermal conductivity and thermal diffusivity tensor components at simultaneous influence of formation temperature and pressure, (7) difficulties with the measurements of coefficient of linear thermal expansion at elevated temperatures (up to 250^0C) with measurements within every narrow temperature intervals ($15-25^0C$) that did not allow to determine a temperature dependence of the parameter.

A set of new equipment has been developed by us to remove these disadvantages and provide qualitatively new possibilities to get numerous reliable data on the thermal properties from the measurements on cores and fluids. Exploitation of these instruments has discovered new chances to test existing theoretical models, enhance these models and develop new theoretical models for predictions of the reservoir thermal properties when rock samples are absent.

OPTICAL SCANNING TECHNIQUE FOR NON-DESTRUCTIVE MEASUREMENTS ON CORES AT NORMAL CONDITIONS

Optical scanning principle is a relatively new approach to thermo-physical measurements. A series of theoretical and experimental investigations was carried out by us to evaluate its potential, and prototype measuring units were constructed (Popov., 1983, 1984a, 1984b; Popov et al., 1999). The theoretical model of the Optical Scanning Method (OS) 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 (figure 1). The heat source and sensors move with the same speed relative to the sample and at a constant distance to each other. Temperature sensor 1 displays the value of unheated sample surface temperature to take preliminary temperatures of the solids into account. Sensors 2 and 3 display the values of the rise of corresponding maximum temperatures along two parallel lines along the heating line behind the source that allows to determine core thermal conductivity and thermal diffusivity simultaneously from one experiment.

The optical scanning along three non-collinear and non-coplanar directions which are located on two non-parallel planes provides determining the principal values of thermal conductivity tensor 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 non-collinear scans on one face, if this face is not parallel to the foliation.

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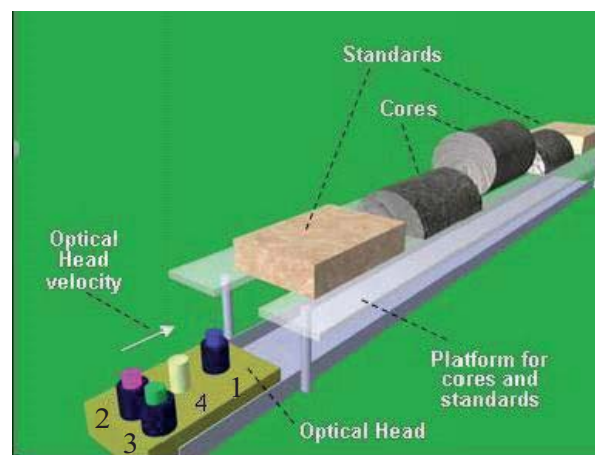

Figure 1: Scheme of a field version of the optical scanning instrument.

Three versions of optical scanning instruments have been elaborated: (1) the field version for numerous measurements of the thermal conductivity and thermal diffusivity on full cores in laboratory and core storages (figure 2), (2) the laser version for measurements of the thermal conductivity and high resolution heterogeneity profiling (with a spatial resolution of 0.2 mm) on full cores (figure 3), and (3) the laser version for the measurements of the thermal conductivity and thermal diffusivity on core plugs and small pieces of rocks (up to 1x1x1 cm) (figure 4). The laser (or focused electric bulb) heat source and infrared radiometers for measurements of initial temperature and temperatures of the heated samples placed on a platform move at a constant speed relatively to the samples and reference standards. Measurements can be carried out on dry or fluid-saturated samples. In the case of cylindrical samples, scans are oriented along the core axis or 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 based on results from reference standards with a similarly rough

surface. The working surface of the sample is covered with an optical coating (25-40 µm thick) in order to minimize the influence of varying optical reflection coefficients. Sample sizes in this study varied 1-70 cm in length, 2-30 cm in width, and 1 and more centimeters in thickness.

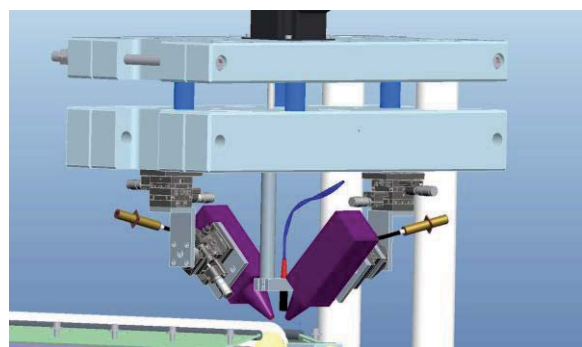*Figure 2: Optical scanning instrument for rock thermal property measurements on full cores.*

Figure 3: Laser optical scanning instrument for rock thermal property measurements and high resolution heterogeneity profiling on full cores.

Figure 4: Laser optical scanning instrument for rock thermal property measurements on core plugs.

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 2-3 cm or more for samples with thermal conductivity exceeding 6-7 $W \cdot m^{-1} \cdot K^{-1}$. 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,
- the effective thermal conductivity and thermal diffusivity of each sample for two mutually perpendicular directions and the related macro-anisotropy factor,
- the thermal inhomogeneity factor defined as standard deviation of thermal conductivity values in thermal conductivity profile recorded along the rock sample during the scanning.

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

A special cell was developed to study thermal properties of non-consolidated rock samples with the optical scanning technique. The cell has a parallelepiped shape with dimensions 110×65×65 mm. A centrally placed cut on the bottom of the cell is covered with a special thin synthetic film which is used for the routine optical scanning technique application. To provide the conditions similar to *in-situ* conditions every non-consolidated sample is compressed with pressure from 0.5 to 1.5 bar during the measurement procedure.

Our results of measurements on more than 80 000 cores from wells (including the scientific deep wells) drilled in different geological structures including geothermal energy fields have shown that rock's thermal conductivity correlates well with porosity, electric resistivity and acoustic velocities and is essentially anisotropic in most cases and varies in rock formations significantly (often by several times) even within cores and short depth intervals (several meters) in formations.

INSTRUMENT FOR MEASUREMENTS OF THERMAL PROPERTIES OF ROCKS AND MINERALS AT FORMATION PRESSURE AND TEMPERATURE

An instrument for measurements of rock's and mineral's thermal conductivity and thermal diffusivity with simultaneous influence of temperature (up to 250 ^{o}C), 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
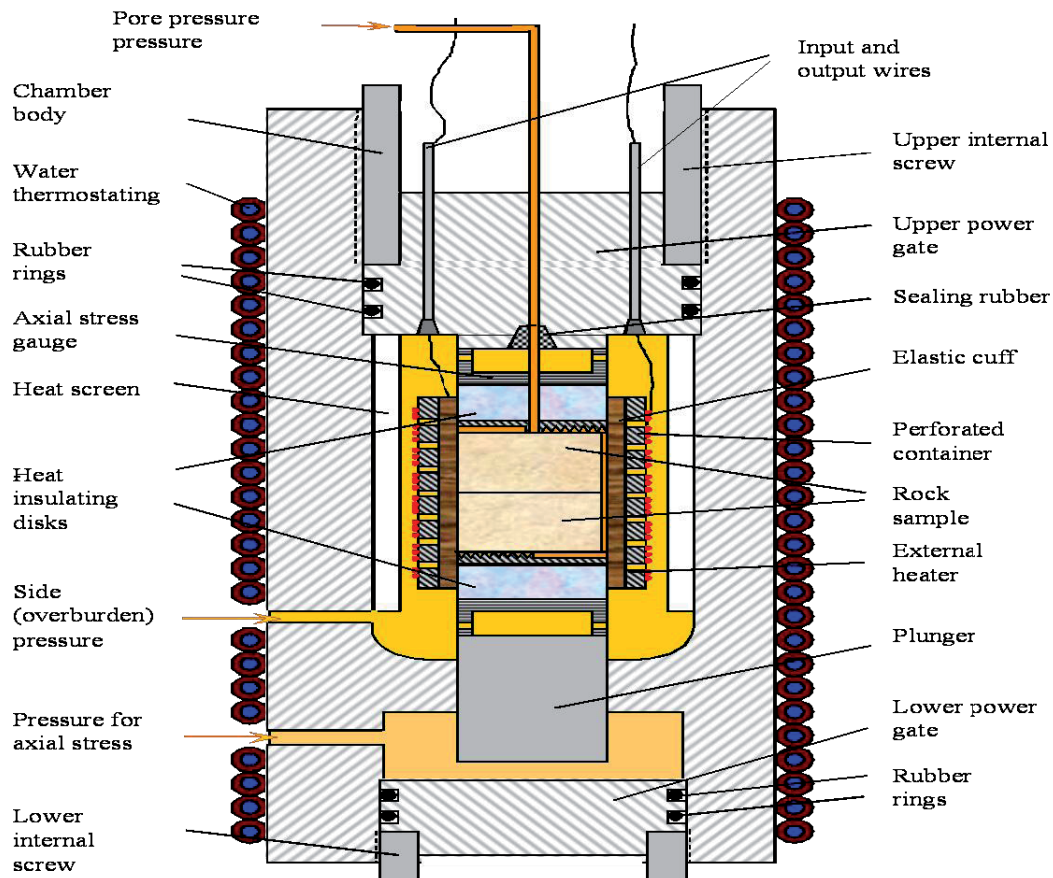
Figure 5: Scheme of chamber for thermal conductivity and thermal diffusivity measurements at simultaneous acting elevated temperature, pore and two components of confining pressure.

figure 5. A new approach in line-source method has been suggested to provide simultaneous measurements of thermal conductivity and thermal diffusivity tensor components within one measurement cycle (figure 6).

The metrological studying of the instrument is a complicated problem as no reliable corresponding references exist now and Standard Bureaus could not help to solve the problem. In our case the instrument metrological testing has been performed on set of 6 reference samples (glasses studied in industrial thermal physics) and a quartz single crystal with thermal conductivity and thermal diffusivity values within ranges of respectively 0.71-10.7 W·m^{-1}·K^{-1} and (0.557-5.42) ·10^{-6} m^2/s at simultaneous influence of elevated temperature and pressure. The quartz single crystal has been used as a reference of anisotropy of thermal conductivity and thermal diffusivity. From the previous study of quartz single crystals of different natural types as reference samples it was established that thermal properties of quartz single crystals are stable independently on their origination (Beck et al., 1977; Beck, 1987;

Popov et al., 1987, 1999). Quartz thermal conductivity values were found from the consistent experimental data at room temperature determined by Beck (1987) (6.07±0.10 W·m^{-1}·K^{-1} for the A and B axes and 10.5±0.1 W·m^{-1} K^{-1} for C axis) and Popov et al. (1987, 1999) (6.05±0.05 W·m^{-1}·K^{-1} for A and B axes and 10.7±0.1 W·m^{-1}·K^{-1} for C axis).

Thermal conductivity of the quartz single crystal was measured with the new apparatus with the line sources oriented in two directions relatively 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

$$\lambda^* = \sqrt{\lambda_{a,b} \cdot \lambda_c}$$ (Popov et al., 1999). The thermal

conductivity tensor component λ_c can be determined from these two measurements. The measurements on

quartz single crystal allowed to test applicability of the instrument developed for measurements of thermal conductivity and thermal diffusivity tensor components on one rock sample. The thermal conductivity and thermal diffusivity tensor components values measured with the new PT instrument at normal conditions simultaneously with two line sources, oriented perpendicularly each to other, were found to be $\lambda_{a,b}$=5.98 W·m^{-1}·K^{-1} in the direction perpendicular to the main optical axis C and λ_c=10.5 W·m^{-1}·K^{-1} in parallel direction that corresponds satisfactorily to the thermal conductivity values established earlier and mentioned above (Beck, 1987; Popov et al., 1987). As for thermal diffusivity values, they have been found to be equal to $a_{a,b}$=2.97·10^{-6} m^2/s and a_c=5.18·10^{-6} m^2/s.
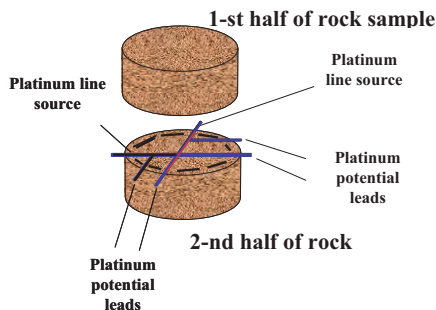

Figure 6: Scheme of rock sample and measuring cell components for simultaneous measurements of thermal conductivity and thermal diffusivity tensor components at elevated PT conditions.

Results of simultaneous measurements of thermal conductivity tensor components at normal thermodynamical conditions and at elevated temperature (up to 130°C) and confining pressure (up to 130 MPa) compared with experimental data reported by Beck et al (1977) are presented on figure 7. From the comparison of the new and published (Beck et al 1977) experimental data for elevated PT conditions one can conclude that these thermal conductivity values coincide well (within both measurement errors).

From testing the instrument on quartz single crystal at simultaneous influence of elevated temperature and pressure, total accuracy+precision value of thermal conductivity and thermal diffusivity measurements has been established to be correspondingly 4 and 7% (at confidence probability of 0.95).

Behavior of thermal conductivity and thermal diffusivity tensor components of quartz, calcite and potassium feldspar single crystals have been registered at simultaneous influence of temperature (up to 220 ^{o}C) and confining pressure (up to 200

MPa). Analysis of experimental data and comparison with literature data have revealed that 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.
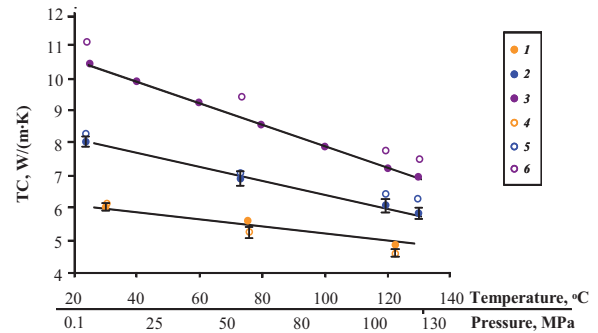

Figure 7: Metrological testing the HPHT instrument: comparison of thermal conductivity tensor components $\lambda_{a,b}$ – (1, 4), λ_c – (3, 6) and

$$\lambda_{app} = \sqrt{\lambda_{a,b}\lambda_c} \ – (2, 5), \ measured \ by:$$

1, 2, 3 – the new instrument, and 4, 5, 6 – by Beck et al. (1977).

The performed metrological study described above can not be considered as comprehensive in respect to carefulness of metrological studying but nevertheless it provides some rough reliability of the routine measurements on rock samples.

Totally 324 sedimentary and crystalline rock samples (with porosity ranged respectively 0.2-39 and 0.1-3%) have been studied at simultaneous influence of temperature and pressure. According to the measurement results for sedimentary rocks at elevated temperature (25-220) ^{o}C 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 ^{o}C by -9…-51% and -13…-66% respectively.

Results of thermal property measurements on crystalline rocks at elevated temperature (25-120) ^{0}C and equal vertical and horizontal components of lithostatic pressure have shown that thermal conductivity and thermal diffusivity vary at pressure of 170 MPa and temperature of 120 ^{o}C by -6…-34 % and -11…-45% respectively.

The experimental setup for thermal property measurements under formation conditions described above was modified to perform thermal properties measurements on non-consolidated rock samples (i.e., sands) at reservoir pressure up to 25 MPa and temperatures within the range of 5…250 ^{o}C. The modified setup allows the measurements on non-

consolidated rock samples in the dry and saturated states with different filling fluids (brine or oil). From a metrological testing of the setup the following parameters were estimated: (1) precision is 3.5%, and (2) accuracy does not exceed 5%. The modified measurement cell for studying non-consolidated rock samples at elevated pressure and temperature is shown in figure 8.
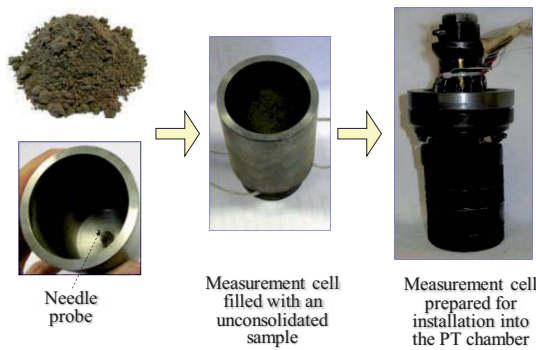

Figure 8: Modified measurement cell for studying non-consolidated rock samples at elevated pressure and temperature.

INSTRUMENT FOR MEASUREMENTS OF THERMAL PROPERTIES OF FLUIDS AT ELEVATED TEMPERATURES AND PRESSURES

A new technique for the measurements of the thermal properties (thermal conductivity and thermal diffusivity) of fluids was developed. The technique is based on the transient hot-wire method (THW) Developed instrument allows the measurements of the thermal properties of fluids under elevated temperature and pressure conditions (temperatures ranges from -25 to 180 ^{o}C and pressure range is from normal to 50 MPa). The approach was found to eliminate the influence of fluid convection effect which disturbs the measurement results usually (Novikov et al., 2009) and provide simultaneous measurements of thermal conductivity and thermal diffusivity with satisfactory quality of the measurements taking into account that even for the best existing experimental setups an accuracy+precision value of the thermal diffusivity measurements is about an order of magnitude higher than the thermal conductivity measurement quality (Khayet, et al., 2005).

A design of the developed experimental cell is shown in figure 9. Main elements of the cell are as follows: 1 – hastelloy cell with the fluid under study coupled with heating/cooling annulus, and 2 - thermostatic unit. The metal "hastelloy" was chosen to prevent corrosion of the cell when chemically active fluid is studied. There is the hot-wire assembly installed

vertically inside the cell. Desired temperature is provided with thermostatic unit and pressure is supplied through high pressure channel.

The transient hot-wire method assumes application of thin platinum wire as the heater and temperature sensor simultaneously. The platinum wire used for heating is 0.1 mm in diameter and potential taps are 0.05 mm in diameter. A 4-wire scheme is used for resistance measurements during heating that allows to exclude a non-controllable resistance of leading wires. The temperature is determined via measured resistance. Acquisition frequency used is as high as 83 Hz (12 ms/sample) that allowed us significantly to decrease an error in the thermal diffusivity measurements.

Figure 9: General view of the cell for thermal properties of fluids measurements under high temperature and pressure: 1 – hastelloy cell with the fluid under study coupled with heating/cooling annulus, and 2 - thermostatic unit.

The technique was metrologically tested on different fluids with well-known thermophysical properties. The results of measurements on distilled water and ethylene glycol over the range 10÷90 ^{o}C at atmospheric pressure (P=0.1 MPa) are presented on figure 10. Deviation from the reference data from National Institute of Standards and Technology (Lemmon et al., 2005) is about ±1.5% for thermal conductivity and ±3% for thermal diffusivity of water. Unlike water, one observes at least 5% deviation in different published data for ethylene glycol. The data from (Microelectronics Heat Transfer Laboratory, 1997) was chosen as a reference data for ethylene glycol. In this case an observed deviation is about 0…2.5% for thermal conductivity and -2…+8% for thermal diffusivity. That can be explained, at the first, by other conditions of the
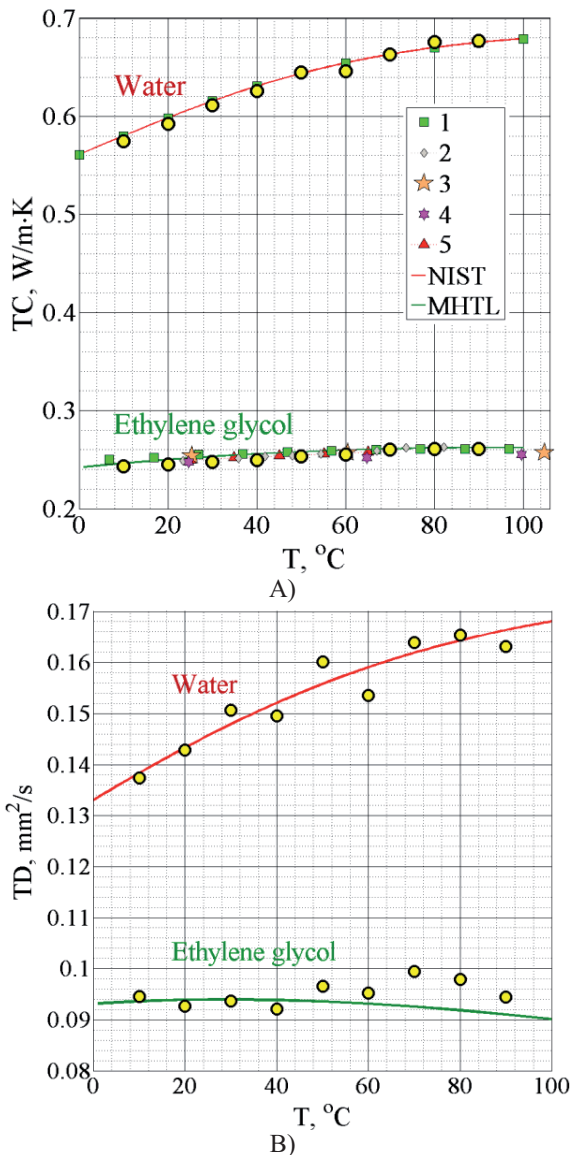
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Figure 10: Thermal conductivity (A) and thermal diffusivity (B) variations vs temperature for distilled water and ethylene glycol. Comparison of our measurements (solid circles) with literature values. Markers 1, 2, 3, 4 and 5 represent data from (Vargaftik et al. 1990), (Assael et al., 1989), (DiGuilio and Teja, 1990), (Bohne et al., 1984), and (Khayet et al., 2005) correspondingly; the solid curves represent the reference data from NIST (Lemmon, et al., 2005) and MHTL (Microelectronics Heat Transfer Laboratory, 1997).

experiment executed, and, secondary, by lack of standards for the ethylene glycol. Mean deviations of the measurements results with the new instrument from the reference data are 1.4% for thermal conductivity and 3.1% for thermal diffusivity for ethylene glycol, and correspondingly 0.9% and 1.7% for water.

INSTRUMENT FOR MEASUREMENTS OF LINEAR THERMAL EXPANSION COEFFICIENT OF ROCKS

A new quartz dilatometer for the measurements of the coefficient of linear thermal expansion (CLTE) of rock and mineral samples was elaborated to meet the following technical requirements:

(1) possibility of CLTE measurements on core plugs (cylinders with length of 30±5 mm and diameter of 30±1 mm) used for measurements of other petrophysical properties (porosity, permeability, sonic velocity, electrical resistance, etc.);
(2) possibility of determination of CLTE tensor components (anisotropy studying) on one cubic sample placed in the instrument in three different directions;
(3) measurements of sample surface temperature during CLTE determination instead of recording temperature in some space between the sample and furnace wall to provide more accurate sample temperature determination;
(4) extension of the CLTE range studied to the CLTE range of rocks and rock forming minerals;
(5) following to the basic requirements of the ASTM Standards (ASTM D 4535-85(2000) and ASTM E 228-95) concerning displacement sensor sensitivity, rate of rock heating and cooling and measurement procedure.

The overall view of the new instrument is presented in figure 11.

The measuring cell of the quartz dilatometer is shown in figure 12.

The instrument provides the measurements of the differential CLTE values for every temperature interval of 20 ^{0}C that allows us to establish a regularity in the CLTE variations within the temperature range of 20-250 ^{0}C with a temperature step of 20 ^{0}C.
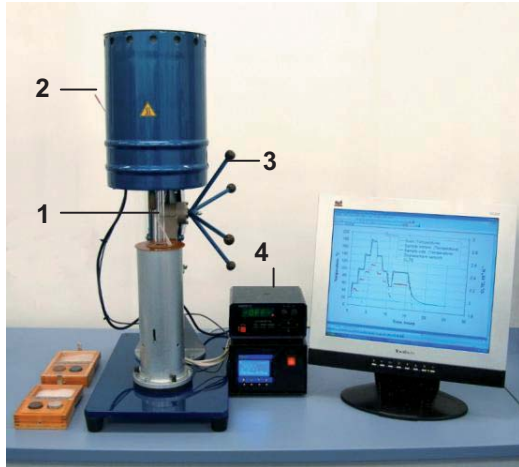
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Figure 11: The quartz dilatometer for the measurements of the coefficient of linear thermal expansion on rock samples: 1 - specimen holding system of vitreous silica; 2 – furnace; 3 – lifting system; 4 – temperature controller and thermal displacement indicator.

Theoretical modeling temperature field of rock samples during heating and cooling accounting for the instrument construction parameters has allowed us to estimate temperature gradient values within rock samples for the sample dimensions chosen and different thermal properties (thermal conductivity, thermal diffusivity and specific heat capacity) at different heating and cooling rates. To validate the modeling results the special experiments were performed when thermocouples were installed at different points of rock samples on external surfaces as well in a sample center. That allowed us to conclude that parameters of heating and cooling regimes are in the agreement with the ASTM standard D 4535-85 (2000): (1) heating and cooling rates are not higher than 1 K/min, and (2) temperature gradient along the sample axis does not exceeds 0.5 K/cm at a stable temperature level.

Metrological testing the CLTE instrument developed was performed on a certified reference standards (fused quartz, silicon single crystal, cuprum, aluminium) with the CLTE values within the representative range of $(0.5-24.6)\cdot10^{-6}$ K^{-1}, that covers in general a range of rock and mineral CLTE values $(2.5-18)\cdot10^{-6}$ K^{-1}.

From numerous measurements on the set of CLTE references, a relative accuracy+precision value was established to be not more than ±4% for every 20 °C interval.

The technical specifications of the quartz dilatometer are listed in Table 1.
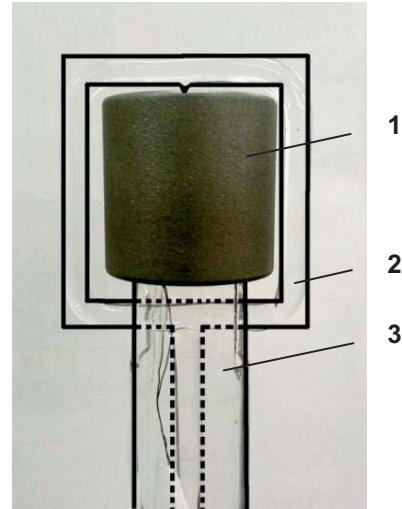

Figure 12: The measuring cell of the quartz dilatometer for the measurements of the coefficient of linear thermal expansion on rock samples: 1 - core plug sample under study; 2 – movable quartz rod; 3 – specimen holding tube of vitreous silica.

Table 1. Technical specifications of the quartz dilatometer.

Sample shape and dimensions	Cylinder (standard core) and cubes with characteristic size of 30 mm
CLTE range, K^{-1}	$(1…25)\cdot10^{-6}$
Temperature range, °C	20…250
Temperature sensors	Chromel-alumel thermocouples
Accuracy+precision of sample temperature control, °C	±0.2
Extensometer type	Inductive
Displacement resolution, mm	10^{-5}
Pressure, MPa	0.1
Absolute accuracy+precision of rocks CLTE measurements, K^{-1}, *for temperature step 20 K*	$±0.1\cdot10^{-6}$
Duration of automatized CLTE measurement for one rock sample with full cycle of heating and cooling (CLTE hysteresis recording)	12 hours

The measurements on a quartz crystal have shown that the discrepancy is observed between previous and experimental data on the quartz CLTE. The

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current data obtained from the new instrument application exceeded the previous data (Clark 1966; Raz et al. 2002) by 20%.

A small accuracy+precision value and possibility to determine the CLTE value for every 20 ^{o}C temperature interval allowed us to establish the CLTE vs temperature dependences within a temperature interval of 20 to 100 ^{o}C, which was chosen to prevent rock sample destruction, for samples of different rock types.

From the measurements on core collections it was established that the CLTE values for carbonates range from (3.48 to 10.8)$\cdot 10^{-6}$ K^{-1} at 30 ^{o}C to (4.50 to 14.4)$\cdot 10^{-6}$ K^{-1} at 100 ^{o}C, for quartz sandstones they range from (7.3 to 11.5)$\cdot 10^{-6}$ K^{-1} at 30 ^{o}C to (9.6 to 13.2)$\cdot 10^{-6}$ K^{-1} at 100 ^{o}C.

THEORETICAL MODELS FOR THERMAL CONDUCTIVITY ESTIMATION

Theoretical prediction of the thermal conductivity is of importance in prospecting geophysics since this property is related to "nonmeasurable" one at the field scale. Two ways exist for the theoretical prediction of this property. The first way is to use empirical relations between the thermal conductivity and other physical properties that can be measured at the field scale (e.g., elastic wave velocities or/and electrical conductivity). However, these relations are specific for particular rock type, its age, and even place. The second way is to use theoretical methods that relate the rock's (effective) thermal conductivity with the properties of its components. The majority of these methods predict the rock's thermal conductivity from the volume concentration and thermal conductivity of its components. Among these methods the most popular is the Lichteneker method calculating the effective thermal conductivity as the geometrical mean of the components (Lichteneker, 1931; Pribnow and Sass, 1995). However, for porous-cracked rocks one of the major factors controlling the effective thermal conductivity is the shape of voids. Nowadays, an approach has been developed incorporating the shape effect into the effective thermal conductivity. This approach is based on the effective medium theory and allows one to consider different shape of heterogeneities representing them as ellipsoidal inclusions from very thin oblate ellipsoids (penny-shape cracks) to very elongated spheroids (needle-shape cracks). Besides, this approach is suitable for anisotropic rocks. The assumption on ellipsoidal shape makes it possible to obtain the solution for effective thermal conductivity in the analytical form:

$$X^* = (X(r)[X^c(I-F) + X(r)F]^{-1})([X^c(I-F) + X(r)F]^{-1})^{-1}, \quad (1)$$

where angular brackets mean averaging over the representative volume, X^* is the effective thermal conductivity (tensor of the 2nd rank), $X(r)$ is the coordinate-dependent thermal conductivity tensor having different values for different heterogeneity types, X^c is the thermal conductivity tensor of so-called comparison body reflecting the specific features in pore/crack connectivity, I is the unit tensor, and F is the formation tensor depending on the heterogeneity shape. For statistically homogeneous medium, the volume averaging can be replaced by the statistical averaging. In this case, the distribution function of the void's volume over the aspect ratio is used. This fact gives a possibility to incorporate variability in pore/crack geometry usually observed in reservoir rocks when calculating the effective thermal conductivity.

In addition to solution of the forward problem on effective thermal conductivity determination, the approach based on the effective medium theory allows one to invert the pore/crack geometry and matrix thermal conductivity from thermal conductivity measurements on samples saturated with fluids whose thermal conductivity is known (Bayuk, et al.,, 2011). The formulas for calculating other effective physical properties including the elastic properties and electric, dielectric, and hydraulic conductivity (transport properties) have the form similar to (1). This fact gives an opportunity to use this approach to predict the thermal conductivity from the other physical properties via the pore/crack geometry reconstruction and vice versa (Bayuk, et al., 2011).

CONCLUSIONS

1. The technique and instruments developed provide the measurements of the rock thermal properties and allow to improve a quality of experimental thermal property data for reservoirs and formations.

2. Three modifications of the optical scanning instruments provide high precision of measurements, high speed of operation, contactless mode of measurement, the ability to measure directly on full cores and core plugs as well as on non-consolidated rock samples without mechanical treatment with simultaneous determination of thermal conductivity and thermal diffusivity, thermal anisotropy and estimation of heterogeneity of rocks.

3. Essential thermal heterogeneity of rock formations discovered from the numerous optical scanning measurements demonstrate necessity of the measurements on representative core collections with detailed core sampling along wells.

4. The instrument developed for the rock thermal property measurements at formation conditions allows to determine the thermal conductivity and

diffusivity tensor components at simultaneous influence of elevated temperature and three component pressure (pore, axial and confining pressure components) for consolidated and non-consolidated rock samples.

5. The instrument developed for fluid thermal conductivity and thermal diffusivity measurements provides the measurements for fluids with wide range of viscosity without disturbing influence of thermal convection in low viscous fluids.

6. The instrument developed for the coefficient of linear thermal expansion study provides the measurements the coefficient tensor components on one sample within the temperature range of $20\ldots250\,^{0}C$ with a temperature step of $20\,^{0}C$.

7. The advanced theoretical model of effective thermal conductivity of heterogeneous medium based on the effective medium theory was developed for prediction of the thermal conductivity of rocks.

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