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ISRM SUGGESTED METHOD

ISRM Suggested Methods for Determining Thermal Properties of Rocks from Laboratory Tests at Atmospheric Pressure

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1 Introduction

Thermal properties—thermal conductivity, thermal diffusivity, specific heat, volumetric heat capacity, and thermal effusivity—are fundamental physical properties of rocks and rock-forming minerals. They have clear physical meanings, and two of them (thermal conductivity and volumetric heat capacity) are used in Fourier's heat conduction equation for homogeneous solid:

$$c\rho\frac{\partial T}{\partial t}-\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)=F \qquad (1)$$

where T is temperature in a solid body point with coordinates x, y, z, t is time, c is solid specific heat, ρ is solid density, λ is solid thermal conductivity, and F is a function of heat sources.

Therefore, estimates of thermal conductivity and volumetric heat capacity are required for thermal and thermo-hydrodynamic simulations of heat and mass transfer processes in rock formations.

The characterization of the thermal properties of rocks, which are essentially heterogeneous in nature due to a wide range in properties of constituent minerals, is much more complex than the characterization of the thermal properties of relatively homogeneous artificial materials that are the common focus of industrial design applications. Advances in determining rock thermal properties have been made through the development of a few in situ methods (Burkhardt et al. 1990; Kukkonen et al. 2007); thermal relaxation methods (Wilhelm 1990); various types of logging (Williams and Anderson 1990; Pribnow et al. 1993); and the study of the thermal effects of mineral composition and texture of rocks (Schoen 1996; Bayuk et al. 2011). However, while valuable in specialized applications, these approaches can not match the accuracy and precision of laboratory measurements on rock samples when cores or cuttings are available.

Knowledge of thermal properties of rocks is increasingly important in mining, geotechnical, civil and underground engineering. Thermal properties of rocks play an important role in environmentally sensitive projects such as disposal of high-level radioactive waste in deep underground sites and repositories, or various engineering projects such as the design and installation of buried high-voltage power cables, oil and gas pipe lines, as well as ground modification

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techniques employing heating and freezing. The measurement of thermal properties of geologic materials has received much attention in the past years as a result of growing interest in underground storage (compressed or liquefied natural gas, liquefied petroleum gases, compressed air, oil or water). Heat transfer is an important consideration when building underground structures such as tunnels and subway stations; for underground storage of natural gas and energy; in mining engineering, particularly to solve a problem of ventilation for deep underground mine operation (Ulusay 2012). For example, the accuracy of predictions of subsurface temperatures along proposed tunnels for rail transport systems and hydropower projects depends on how well thermal properties of rock formations are determined (Birch 1950; Rybach and Pfister 1994; Goy et al. 1996; Rybach et al. 2003).

Likewise, for geological disposal of nuclear waste, thermal properties of underground rocks control the dissipation of heat generated by the waste product. Rocks with a higher thermal conductivity are more efficient at transferring heat energy. The accuracy of rock thermal conductivity determination therefore affects the size, layout and cost of the repository system (see for example, Andersson et al. 2000; Kukkonen and Lindberg 1995).

Thermo-hydrodynamic models to evaluate oil recovery from heavy oil reservoirs at temperature ranges from 10 to 300 °C require detailed data on the thermal conductivity and volumetric heat capacity for each relevant formation (Chekhonin et al. 2012; Popov et al. 2010, 2013a, b).

Rock matrix thermal properties for thermo-hydrodynamic modeling (including basin and petroleum systems) require the input of the thermal conductivity and volumetric heat capacity of the matrix material for each formation. The simulators use these matrix values in theoretical thermal conductivity and volumetric heat capacity models to calculate the effective thermal properties of porous rocks from estimates of porosity and predicted pore fluid thermal properties (Popov et al. 2013a, b).

Geothermal energy recovery for power generation and direct use involves injecting fluid through a borehole into the ground, drawing heat from the ground around the borehole by conduction, and the extraction of steam from geothermal fluids directly obtained from boreholes. The thermal properties of the rocks are therefore critical parameters for predicting the lifetime performance of geothermal systems. Studies should focus on characterizing thermal conductivity (including inclination of main axes of the thermal conductivity to the borehole axis in anisotropic formations) of all rocks surrounding the borehole, as well as the thermal conductivity and the volumetric heat capacity of reservoir rocks.

Finally, brief details of specific heat and latent heat determinations are also considered in the present suggested methods. Although the coefficient of linear (or volumetric) thermal expansion is also a rock thermal property, it is not relevant to the description of heat transfer; therefore, the description of techniques for measuring the thermal expansion coefficient falls outside the scope of these suggested methods.

2 Scope

These suggested methods describe important details and considerations that could be used for investigations of the thermal properties of rocks, thus helping to mitigate systematic errors in measurements. Techniques for thermal conductivity and thermal diffusivity/volumetric heat capacity measurements on heterogeneous and anisotropic rock samples are recommended here.

The thermal conductivity (λ), thermal diffusivity (a) and volumetric heat capacity (C) are defined by the relationship $a = \lambda/C$. Thus, any of these three values can be calculated if the other two are known. The specific heat (c) is related to C through the equation $c = C/\rho$, where ρ is the rock density. The thermal effusivity (μ) is related to λ and C through the equation:

$$\mu = (\lambda \cdot C)^{1/2} \tag{2}$$

The thermal conductivity, thermal diffusivity, and heat capacities (specific or volumetric) of rocks are functions of the mineral composition, interstitial porosity, and nature of fluids filling the interstitial pores and fractures. The thermal conductivity and thermal diffusivity of rocks are functions of orientation of fractures and micro-cracks, mineral grain size and orientation, anisotropy of the rock matrix and nature of inter-grain contacts. They are almost always directionally dependent and can be represented by a second-rank tensor. All these properties vary with temperature and pressure.

The volumetric water content of a rock has a strong influence on its thermal properties. The thermal conductivity of water at atmospheric conditions [~0.60 W/(m K)] is much lower than the thermal conductivity of a typical rock matrix [~1.5–7.6 W/(m K)] and much larger than the thermal conductivity of air [~0.025 W/(m K)]. The volumetric heat capacity of water at atmospheric conditions [$\sim 4.19 \times 10^6$ J/(m^3 K)] is larger than the volumetric heat capacity of rock matrix [$\sim (1.7–2.7) \times 10^6$ J/(m^3 K)] and much larger than the volumetric heat capacity of air [$\sim 0.00124 \times 10^6$ J/(m^3 K)]. Measurements of these properties are therefore very sensitive to pore fluid content.

The study of thermal anisotropy is arguably important in all applications related to rock thermal properties measurements. Thermal anisotropy can be caused by a preferred orientation of rock fractures and/or micro-cracks; by a preferred orientation and distribution of rock-forming minerals; and/or by the structural/textural anisotropy resulting from rock layering, bedding, and/or cleavage.

The three methods most commonly used for measuring the thermal properties of rocks at atmospheric conditions are the optical scanning, the divided-bar, and the line-source method. The characteristics of the divided-bar and line-source methods are well understood. They have been applied to measure, in particular, thermal conductivity for many years in rock mechanics, rock engineering and geophysics applications. All these three methods require various degrees of preparation of the rock samples prior to measurement. Samples are preferably in the form of drill cores, core plugs, and less preferably drill cuttings.

The most effective testing method for any rock thermal property measurement depends strongly on the particular requirements of the test. Issues to consider when making a choice should include: the nature of the rocks to be studied (crystalline or sedimentary), saturating conditions, consolidation state (weakly consolidated or well indurated). Where the reservoir or formation heterogeneity needs to be characterized, numerous measurements on full core along a well could be necessary. Sometimes, only the thermal conductivity needs to be measured and occasionally several thermal properties need to be characterized. Requirements to measure the thermal conductivity and thermal diffusivity on the same rock specimen at the same time, the acceptable accuracy and precision of the measurements, the necessity to assess the rock thermal anisotropy and heterogeneity are the key factors that should be accounted for a choice from the methods. The suitability in using a paste to reduce thermal resistance between a rock sample surface and the sensor of a measuring instrument is important as any changes of core samples are often inadmissible.

Although many methods and instruments exist for thermal properties measurements on solids (e.g. hot disk technique (He 2005), flash technique (Parker et al. 1961), the test methods and instruments described in the present suggested methods have been widely applied to study natural materials and have been subjected to strict checking and evaluation. Moreover, one of the methods described has been developed specifically for rocks.

The present SM paper describes:

1. General typical requirements to the rock thermal property measurement methods (Sect. 3).
2. The optical scanning, divided-bar, and line-source methods that are most widely used in applied geophysics, geology and mining engineering at present (Sects. 4, 5, 6).
3. Recommendations on metrological testing and control of the measuring techniques (Sect. 7).
4. General features of the measuring techniques (Sect. 8).
5. Information on specific heat and latent heat measurements (Sects. 9, 10).

The structure of Sects. 4, 5 and 6 is identical where theoretical background, experimental set-up, specimen preparation, measurement procedure and data processing, reasons for possible errors and metrological peculiarities are described for each test method.

3 Requirements for Rock Thermal Properties Measurements

For the continental scientific deep drilling program, in the former Union of Soviet Socialist Republics (USSR) since 1970 many super-deep and deep wells were drilled with extensive, often continuous coring. The subsequent German Continental Deep Drilling Program (with the super-deep well KTB) in Germany (1982–1994), and the International Continental Scientific Drilling Program (ICDP) initiated in 1996, required vast data on rock thermal properties. This need stimulated the evolution of thermal petrophysics including comprehensive studies of very large core collections, development of techniques for reliable measurements of thermal properties, and characterization of thermal rock heterogeneity and thermal anisotropy. Development of non-destructive measurement methods had become especially important to preserve irreplaceable and historic core samples.

The increasing importance of thermal property data for geothermal energy production during 1990–2013 also provided motivation for enhancing the development of thermal properties measurements. Since 2000, the advances in heavy oil production, as well as basin and petroleum system modeling, resulted in a sharp increase in the quality of experimental data on rock thermal properties (Chekhonin et al. 2012; Popov et al. 2013a, b). Additional data demands during this period included experimental information for 4D thermal modeling of artificially heated heavy oil reservoirs when 3D spatial variations and corresponding temporal variations of the rock thermal properties should be accounted for. Improved measuring methods were needed to study spatial and temporal variations in rock thermal properties during transient thermal processes.

Investigations were performed during 1983–2013 to select, among many traditional and new techniques, the most effective methods and instruments (Galson et al. 1987; Sass et al. 1984; Sundberg et al. 2003; Popov et al. 1999b). As part of this effort, two international projects tested and compared the optical scanning, divided-bar and line-source methods. The projects were based on numerous thermal conductivity measurements of 80 core samples from the super-deep KTB borehole in Germany and other collections of rock samples, minerals and industrial materials which have been certified by National Standard Bureaus in USA, Germany, and Russia (Popov et al. 1999b). These and many other methods and instruments were drawn in ring tests on more than 1200 core samples with the participation of laboratories experienced in rock thermal properties measurements.

The following problems typical for the thermal conductivity (and volumetric heat capacity) measurements were identified from these tests and are described below.

1. A 15–50 % underestimation in the thermal conductivity measurements were observed in many cases, especially for high-porosity and fractured sedimentary rocks when rock samples cannot be polished satisfactorily to provide a good contact between rock sample surfaces and measuring instrument components. These underestimates exceeded natural variations in thermal conductivity within rock formations and were caused by an unaccounted thermal contact resistance between the rock sample surface and the instrument component (heater and sensors) surfaces. Errors associated with less than ideal contacts were in many cases more important than errors associated with poor saturation of rock samples (see Sect. 5.8).
2. The difficulty in providing an adequate polished surface of the sample, particularly for highly porous rock samples, required sufficient contact pressure between the measuring instrument components and the rock sample. When testing low strength samples, this often resulted in failure and partial to full disintegration of the samples.
3. Some measurements of 'effective thermal properties' ignored the intrinsic heterogeneity of rock samples.
4. Time-consuming mechanical preparation of rock samples before measurements, and long measurement times, made it difficult to perform enough measurements to assess accurately thermal conductivity variability within formations.
5. Thermal anisotropy of rocks was ignored in most cases. The determination of principal thermal conductivity axes and principal components of the thermal conductivity tensor is very complicated in most cases due to the influence of rock heterogeneity when several rock sample parts with different orientations are used to solve the problem. The problem is especially serious when three (for 3D anisotropy) or two (2D anisotropy) rock samples with orientation along different principal axes of anisotropy are prepared and used for the determination of thermal conductivity and thermal diffusivity tensor components.
6. Special liquids or pastes were used to reduce the thermal resistance between rock sample surfaces and instrument sensors. While applying axial pressure at the contacts to reduce thermal resistance, the paste could penetrate the void spaces of porous and fractured rocks and alter their physical properties. This may have also prevented further petrophysical measurements.
7. Simultaneous thermal conductivity and thermal diffusivity (or thermal conductivity and volumetric heat capacity) measurements could not be provided in most cases.
8. Some rock types (e.g. shales and other thin-schistose rocks) are sensitive to mechanical treatment and change their thermal (and some other) properties essentially (often up to 20 %) during preparation of the samples with special forms and dimensions according to the measuring equipment requirements.

Many laboratories have tried to develop their own experimental techniques relying on metrological tests on industrial materials (glasses, metals, ceramics, plastics, etc.). These materials are usually isotropic, homogeneous, easily polished or surface-treated mechanically, and can be subjected to contact pressure without any damage. However, they are non-representative of rocks and geologic formations, which are heterogeneous, with distinct porosity (interstitial/fractures), stress-sensitive, and exhibiting a broad range of strengths. A common misconception for rock mechanics, rock engineering and geophysical applications is that thermal properties measuring equipment developed for the study of thermal properties of industrial materials is adequate.

Rocks are discontinuous or porous, heterogeneous, anisotropic and often require numerous measurements on various sized samples (e.g. full size cores, core plugs), may be stress-sensitive, require saturation control, and cannot be polished satisfactory as required for contact thermal measurements. Additional challenges particular to rock measurement include poor metrological support from National Standard Bureaus for testing rocks and a limited set of reference standards (industrial materials) and reference rock samples with well-defined thermal properties.

Several other requirements and recommendations for the measurement of thermal properties of rocks regarding the types of rocks and samples are addressed in the following paragraphs.

3.1 Arbitrary Natural Rock Samples

All the methods recommended below require, at least one smooth rock surface (flat or cylindrical). The samples should be prepared in such a way that: (1) they meet the recommended requirements for one of the methods described below, (2) they retain their natural integrity as far as possible, (3) the measurements are appropriate in addressing the intended scientific and engineering questions.

3.2 Full Size and Split Cores

Measurements on full size core are recommended whenever possible to prevent additional (often serious) changes in the core physical properties. If original core samples are sawn and split along their drill axis, thermal properties measurements on the flat surfaces of split core are preferable without any additional mechanical treatment to fit rock samples size for measuring equipment that is often required in the application of many traditional measuring techniques.

3.3 Core Plugs

Core plugs are cylindrical rock samples (for example 30 mm diameter × 15 mm length) that are prepared for routine standard petrophysical measurements (Jarrard 2001). Measurements on core plugs accounting for rock anisotropy provide an appropriate method for studying correlations between thermal properties, rock fabric, and other physical properties. All properties should be measured on the same rock sample to prevent rock heterogeneity and anisotropy from influencing relevant correlations (Popov et al. 2003b).

3.4 Weak and Poorly Consolidated Rocks

Any influence (i.e. stress, surface grounding, etc.) that may alter the natural pore/crack structure of the sample and change its thermal properties must be avoided prior to and during thermal properties measurements. The same requirements apply to measurements on high-porosity and/or fractured sedimentary rocks, saturated with brine and/or oil.

3.5 Drill Cuttings and Rock Fragments

Measurements on drill cuttings are sometimes necessary to supplement cored sections or when a well is drilled with reverse circulation without coring. Rock fragments from diverse sources can also be used for thermal properties characterization when consolidated core samples are absent.

3.6 Single Crystals of Rock-Forming Minerals

The thermal properties of rock-forming minerals are best characterized by measuring the 2D or 3D thermal anisotropy of single crystals. Uniqueness of samples of minerals does not allow any mechanical treatment of samples for thermal characterization of single crystals of minerals in most cases. The small size of single crystals also in many cases prevents thermal properties measurements in part explaining why current databases of thermal properties of rock-forming minerals are sparse, often of poor quality, and sometimes contradictory. Numerous non-destructive measurements on single crystals with thermal conductivity anisotropy characterization have only recently become possible (Popov et al. 1987).

3.7 2D and 3D Anisotropic Rock Samples

Experience has demonstrated that most rocks exhibit thermal anisotropy (e.g. Popov and Mandel 1998; Fuchs et al. 2013; Jorand et al. 2013). Therefore, measurements of the principal thermal conductivity tensor components for 2D or 3D anisotropy are relevant for most types of rocks. Whether the directions of the principal axes of thermal conductivity are known or not, the measuring technique must provide the determination of the principal thermal conductivity tensor components and the direction of the principal axes.

3.8 Heterogeneous Rock Samples

Most crystalline and sedimentary rocks are intrinsically heterogeneous. Variability of rock thermal conductivity within a sample is caused by spatial variations in porosity (interstices/fractures), mineral composition, inter-grain contacts and pore space geometry. These are the reasons why local thermal conductivity values can typically vary by 10–30 % from its average value. Assessing heterogeneity poses further constraints on an appropriate measuring technique. Characterizing the thermal heterogeneity of individual rock samples provides additional petrophysical information for reservoir and formation evaluation.

At present no single technique satisfies all the abovementioned requirements. The optical scanning, divided-bar, and line-source methods have proven to be the more reliable and accurate for rock thermal properties measurements. They are widely used in applied geophysics, geology and mining engineering, and they will be addressed in the following sections. There are other methods and instruments developed for measurements of the thermal properties of solid materials [e.g. flash technique (Parker et al. 1961), hot disk (He 2005), 3ω techniques (Jacquot et al. 2010)], but these are less common in mining engineering, geology and geophysics and so they will not be reviewed here.

4 Optical Scanning Technique

The optical scanning method was designed especially for rock thermal properties measurements (Popov 1983). Physical discrepancies between theoretical models and experimental realization of the method were studied in details (e.g. Popov 1983, 1984, 1997; Popov et al. 1985). Important characteristics of the optical scanning method are as follows: (1) simultaneous determination of thermal conductivity and thermal diffusivity (hence volumetric heat capacity) in one experiment, (2) absence of contact between the instrument sensors and the rock sample, (3) ability to measure full size core, split core, broken core with one smooth surface and core plugs without any additional mechanical treatment, (4) ability to determine thermal conductivity and thermal diffusivity anisotropic tensor components for every rock sample studied, (5) ability for continuous profiling of thermal properties to investigate thermal heterogeneity related to the structural and textural characteristics of rocks, (6) high speed of operation and short measuring time, (7) flexibility in spatial resolution and penetration depth of measurements by changing the scanning velocity and heater–sensor separation, (8) wide range of sample lengths accommodated (from 8 to 900 mm).

Between 1982 and 2009, the optical scanning technique was used to measure the thermal properties of >30,000 core samples from 15 deep scientific wells in seven countries. Early thermal conductivity and thermal diffusivity measurements on core sampled every 1–2 m within a borehole provided surprising experimental results with respect to vertical specific heat flow (SHF) (Popov 2012; Popov et al. 1999a, 2003a). Significant variations (up to 130 %) in vertical SHF were inferred within a single borehole, and a systematic increase (30–130 %) in terrestrial SHF values was established for deep boreholes (drilled within the Russian Scientific Deep Drilling Program, KTB and ICDP programs) and compared to previous experimental results for the same areas (for examples see Popov et al. 1999a, 2003a; Popov 2012). These results prompted an international program of testing of the optical scanning technology. The optical scanning measurements were compared against the thermal conductivity measurements made using more than ten alternate methods and fourteen certified thermal conductivity standards (from National Standard Bureaus in USA, Germany and Russia) and more than 1200 rock samples (e.g. Popov et al. 1999b). Results of numerous thorough tests confirmed the optical scanning parameters given in Table 1 and prompted a worldwide adoption of the optical scanning technique for petrophysical studies. The optical scanning technique has been officially certified in Russia (a corresponding certificate from Ministry of Geology of Russian Federation, VNIGIK #2, was issued in 18 December 1986).

4.1 Experimental Setup and Technical Parameters

There are three types of optical scanning instruments (Fig. 1) (Popov et al. 2013a, b). All three of the instruments are based on the same measurement principle (see 4.2) and working scheme given in Fig. 2 below. Type 1 is used for simultaneous measuring and profiling of thermal conductivity and thermal diffusivity (hence, volumetric heat capacity) on full size and split cores (Fig. 1a). Type 2 is used for simultaneous measuring and profiling of thermal conductivity and thermal diffusivity (and volumetric heat capacity) on standard core plugs and rock fragments (Fig. 1b). Type 3 is experimental equipment used in research but currently not commercially available. It allows simultaneous measuring and profiling of thermal conductivity and thermal diffusivity (and volumetric heat capacity) on full size and split core, core plugs, pieces of broken core, and drill cuttings (with dimensions $>6 \times 8 \times 8$ mm). Type 3 provides high spatial resolution of measurements (>0.2 mm) along scanning lines (Fig. 1c). Each type of optical scanning instrument comprises (1) a focused optical heater (an electric lamp in Type 1, and a laser source in Types 2 and 3), (2) three or four infrared sensors, (3) a cradle to hold the optical head, (4) a linear motion system, (5) two reference standards with known thermal properties, and (6) an electronic and power unit. Technical parameters of the different types of optical scanning instrument are given in Table 1. Different functional capabilities and technical parameters of three types of the instruments are provided by different engineering design, variations in parameters of the measurement regime and different types of the optical components (a heat source and infrared sensors).

4.2 Theoretical Background

The essential elements of an optical instrument for measuring thermal properties are illustrated in Fig. 2, where a flat surface of a rock sample (5) is heated by a focused, mobile and continuously operated optical heat source (4) mounted with an array of three infrared temperature sensors (1, 2 and 3). Here, x_0 is the distance between the heating area (point O) and the field of view of infrared sensor 2 located on scanning line 6, and y_0 is the distance between scanning line 6 and line 7 where the field of view of the infrared sensor 3 is moving. The optical head holding the heat source and infrared sensors is moved at a constant velocity relative to the rock sample such that the

Table 1 Technical parameters and features of different types of optical scanning instruments

Parameter	Type 1	Type 2	Type 3
Accuracy*; precision* (%)			
Thermal conductivity	±2; ±1.5	±1.5; ±1	±1.5; ±1
Thermal diffusivity	±2.5; ±2	±2.5; ±2	±2.5; ±2
Volumetric heat capacity	±3.5; ±3	±3; ±2.5	±3; ±2.5
Measured thermal property ranges			
Thermal conductivity [W/(m K)]	0.2–45	0.2–45	0.2–45
Thermal diffusivity (mm^2/s)	0.092–5.0	0.092–5.0	0.092–5.0
Volumetric heat capacity [MJ/(m^3 K)]	0.8–4.0	0.8–4.0	0.8–4.0
Spatial resolution of thermal profiling for rock heterogeneity characterization (mm)	4	2	0.2
Spatial resolution of thermal property measurements in local areas (mm)	15	10	6
Maximum total length of scanning line (mm)	500	280	900
Maximum number of samples for simultaneous measurements	13	6	30
Total time of the measurement of one full set of rock samples on platform, (s)	180	70	230
Acceptable dimensions of rock samples studied			
Length (min–max) (mm)	30–500	10–280	8–900
Width (min–max) (mm)	60**—no limit	10–50	8–200
Thickness (min–max) (mm)	30***—no limit	10—no limit	6—no limit
Possibility to vary minimum thickness (and width) of rock sample involved in the measurements	10–25 mm (20–50 mm) with regulation of scanning velocity	6–15 mm (12–30 mm) with regulation of scanning velocity	4–20 mm (8–40 mm) with regulation of scanning velocity and distance 'heater–sensor field of view' temperature sensors
Ranges of thermal properties of reference standards			
Thermal conductivity [W/(m K)]	0.195–45	0.195–45	0.195–45
Thermal diffusivity (mm^2/s)	0.092–5.0	0.092–5.0	0.092–5.0
Measurements of principal thermal conductivity tensor components for every rock sample studied	Yes	Yes	Yes
Nature of rock sample surface under measurement	Any, from core surface after well drilling to polished surface	Any, from core surface after core sawing to polished surface	Any, from core surface after core sawing to polished surface
Form of the rock sample surface under measurement	Flat, cylindrical	Flat, cylindrical	Flat, cylindrical
Requirements to prepare a special form for every rock sample studied	No requirements	No requirements	No requirements
Possibility to perform thermal property measurements on dry and fluid-saturated rock samples	Yes	Yes	Yes

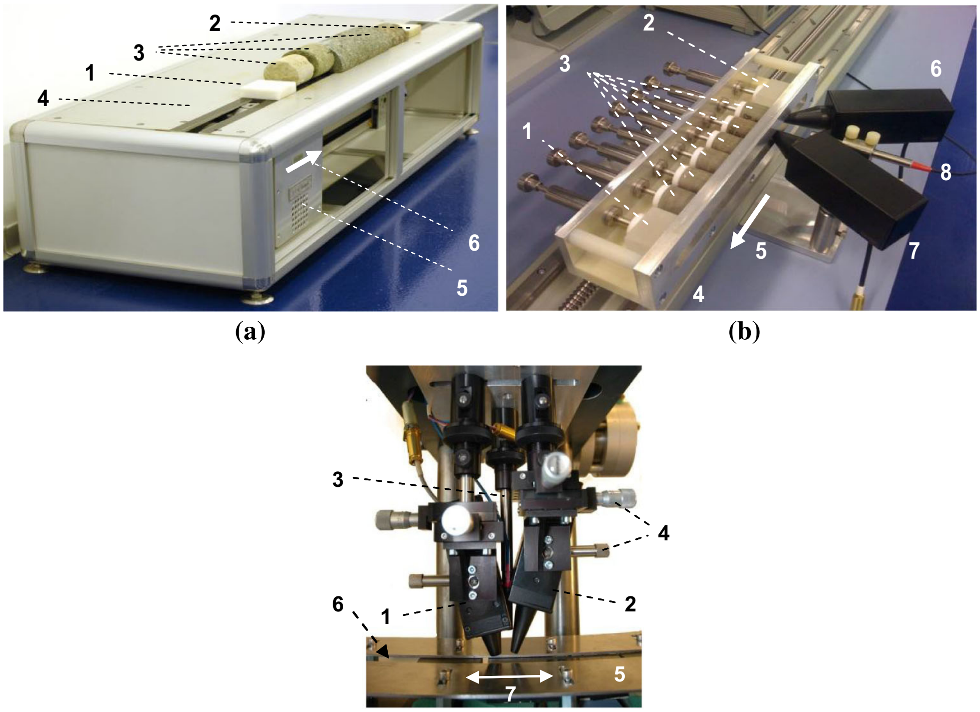
* For a 95 % confidence level

** For rock thermal conductivities smaller than 6 W/(m K); for thermal conductivities between 6 and 15 W/(m K) a width ≥70 mm is required

*** For rock thermal conductivities smaller than 6 W/(m K); for thermal conductivities between 6 and 15 W/(m K) a thickness ≥30 mm is required

heater and sensors follow scanning lines 6 and 7 while maintaining a constant separation.

The method is based on solutions of the thermal conduction equation for a quasi-stationary temperature field in a movable coordinate system OXYZ. The origin, O, of the coordinate system coincides with the location of the heat source on the surface of the solid sample. The axis OZ is perpendicular to the sample surface, and the axes OX and



(a) (b)

(c)

Fig. 1 Types of optical scanning instruments: **a** Type 1 for thermal property measurements on full size core and split core, **b** Type 2 for thermal property measurements on core plugs and pieces of broken core, **c** Type 3 for thermal property profiling at high spatial resolution (~0.2 mm) on full size core, split core, core plugs, pieces of broken core and drill cuttings. The key components of the instruments: Type 1 **a** *1* reference standard 1, *2* reference standard 2, *3* core samples under study, *4* immovable platform for core samples and reference standards, *5* movable optical head with optical heat source and infrared sensors, *6* direction of optical head movement during measurement; Type 2 **b** *1* reference standard 1, *2* reference standard 2, *3* core plugs under study, *4* movable platform with reference standards and core plugs, *5* direction of movement of movable platform with reference standards and core plugs during measurement, *6*, *7* infrared sensors, *8* laser heat source; Type 3 **c** *1*, *2* infrared sensors, *3* laser heat source, *4* adjusting screws, *5* movable platform with core samples, core plugs and reference standards that are located below the platform and pressed to it, *6* slot in platform to open surfaces of core samples, core plugs and reference standards, *7* direction of movable platform with core samples, core plugs and reference standards during measurements

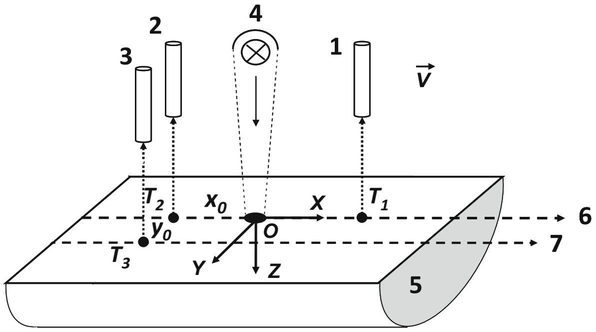


Fig. 2 The essential elements of the optical scanning method for rock thermal properties measurements

OY lie along the flat surface of the sample. When the heat source moves at a constant velocity in the direction of the OX axis, the excess temperatures ($T_2 - T_1$) and ($T_3 - T_1$), defined as differences between the temperatures T_2 and T_3 recorded with sensors 2 and 3 behind the heater and an initial sample surface temperature T_1 recorded with sensor 1 in front of the heater, are described by the equations (Popov 1983):

$$T_2 - T_1 = \frac{q}{2\pi x_0 \lambda} \tag{3}$$

$$T_3 - T_1 = \frac{q}{2\pi\lambda R} \exp\left[-\frac{v(R - x_0)}{2a}\right] \tag{4}$$

where v is the velocity of the heat source across the sample, q is the heat source power, $R^2 = (x_0^2 + y_0^2)$, λ and a are the thermal conductivity and thermal diffusivity of the sample, respectively.

Equation (4) follows from the equation derived for an infinite solid heated by a mobile heat source located at the origin O in a movable coordinate system OXYZ (Carslaw and Jaeger 1959) (see "Appendix" section).

Thus the thermal conductivity and thermal diffusivity of a sample can be determined from Eqs. (3) and (4) provided that two reference standards (with known conductivities λ_{R1} and λ_{R2} and thermal diffusivities a_{R1} and a_{R2}) are scanned in series with the sample (Popov 1983; Popov et al. 1985):

$$\lambda = \frac{\lambda_{R1} \cdot (T_{2R1} - T_{1R1}) + \lambda_{R2} \cdot (T_{2R2} - T_{1R2})}{2(T_2 - T_1)} \tag{5}$$

$$a = \frac{a_{R1} \cdot \ln\left(\frac{\lambda_{R1} \cdot (T_{3R1} - T_{1R1})}{\lambda_{R2} \cdot (T_{3R2} - T_{1R2})}\right)}{\ln\left(\frac{\lambda_{R1} \cdot (T_{3R1} - T_{1R1})}{\lambda_{R2} \cdot (T_{3R2} - T_{1R2})}\right) + \frac{a_{R2} - a_{R1}}{a_{R2}} \cdot \ln\left(\frac{\lambda \cdot (T_3 - T_1)}{\lambda_{R1} \cdot (T_{3R1} - T_{1R1})}\right)} \tag{6}$$

where subscripts $R1$ and $R2$ refer to the reference standards 1 and 2, respectively.

For heterogeneous rock samples with variable thermal conductivity, thermal diffusivity and volumetric heat capacity, the two independent temperature profiles (T_2 and T_3) record the distributions of thermal properties (thermal conductivity, thermal diffusivity and volumetric heat capacity) continuously along every core sample at the spatial resolution of the study.

For anisotropic rock samples, the excess temperature $(T_2 - T_1)$ is determined by the relationship derived by Popov and Mandel (1998):

$$T_2 - T_1 = \frac{q}{2\pi x \sqrt{\lambda_A \lambda_B \cos^2 \gamma + \lambda_A \lambda_C \cos^2 \beta + \lambda_B \lambda_C \cos^2 \alpha}} \tag{7}$$

where α, β and γ are angles between the A, B and C principal axes of thermal conductivity and the scanning line, as illustrated in Fig. 8.

It follows from Eqs. (3) and (7) that the 'apparent' thermal conductivity, that is the measured thermal conductivity, λ_{app}, is determined during every optical scanning measurement of an anisotropic rock sample:

$$\lambda_{\text{app}} = \sqrt{\lambda_A \lambda_B \cos^2 \gamma + \lambda_A \lambda_C \cos^2 \beta + \lambda_B \lambda_C \cos^2 \alpha} \tag{8}$$

4.3 Specimen Preparation

The surfaces of untreated full size core, split or sawn core, and core plugs are all suitable without any mechanical treatment for optical scanning measurements.

The optical scanning method is based on the application of a heat source that is focused at the surface of the rock sample. It is necessary, therefore, to minimize the possibility of optically transparent surfaces transmitting the optical heater radiation into the reference standards and the rock samples. There are several ways to do this: (1) partially coat the surfaces of the reference standards and the rock samples along a scan line with a quick drying enamel paint that does not penetrate deeply into rock fractures and pores (for example, a synthetic enamel) as it is shown in Fig. 3. The paint should be applied with uniform thickness not exceeding 50 µm. The width of the paint strip should be wide enough to cover the heating spot and the temperature sensors field of view (Fig. 2); (2) partially mask the surfaces of the reference standards and the rock samples with a self-adhesive plastic film that is sufficiently opaque to the heater radiation (Fig. 3). The film should be wide enough to cover the heating spot and temperature sensors field of view; (3) perform thermal properties measurements without any surface coating on the reference standards or the rock samples if both are non-transparent to the heater radiation (Popov 2015). A correction factor may be required for thermal properties measurements in case (3), which can be easily assessed by comparison with results using case (1) or (2).

The optical scanning measurements can be performed on any surface of core plugs (Fig. 3a), on cylindrical surfaces of full size core (Fig. 3b), on a flat cross section of a full size core, on the flat surface of split core (Fig. 3c, d), or on prepared flat surfaces of any other rock sample. No correction due to the influence of the surface geometry is necessary for measurements on the cylindrical surface of core diameters larger than 60 mm for instrument Types 2 and 3. For instrument Type 1, no corrections are necessary for sample diameters larger than 80 mm. For smaller diameters, a correction coefficient should be established by comparing, for the same core sample, measurements on its cylindrical and its flat surfaces; this should be carried out on several typical cores.

Sometimes the thermal properties of the external surface layer of a full size core can differ slightly from the properties of the internal part of the core because of core surface damage associated with drilling (Popov et al. 1999b, 2003a). If the rugosity of the core surface exceeds ±0.5 mm, it can introduce a further systematic deviation of a few percent in the measurement results. The thermal conductivity and thermal diffusivity measured on a cylindrical surface can be 4 % less than for a flat surface if the core samples are studied in a water-saturated condition, and 7 % less for dry core samples; this is due to the two effects mentioned above (Popov et al. 2003a). The systematic difference caused by core damage is less for water-saturated samples than for air-saturated samples because the contrast in thermal conductivity between the rock matrix and the pore fluid is less for water than for air (Popov et al. 2003a). The observed differences in measured thermal properties allow for a systematic correction to measurements on cylindrical surfaces of dry and water-saturated cores.

The optical scanning technique allows measurements of anisotropic thermal properties on flat surfaces of single crystals of rock-forming minerals. In this case, thermal conductivity and thermal diffusivity tensors components can be determined. If the crystal faces are smooth and large enough to meet the minimum requirements for the optical scanning system (Table 1), then the method does not

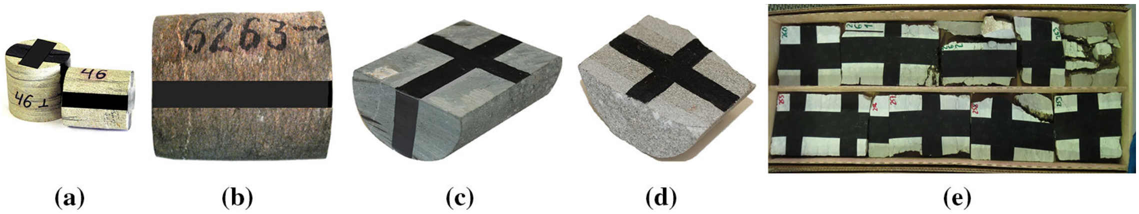


Fig. 3 Preparation of rock sample for the thermal properties measurements with the optical scanning technique. **a** Core plugs (for instruments Types 2 and 3), **b** cylindrical full size core sample (for instruments Types 1 and 3), **c** split core sample with three scan lines for 3D anisotropy study (for instruments Types 1 and 3), **d** split core for 2D anisotropy study (for instruments Types 1 and 3), **e** a box with split cores for continuous thermal core logging (for instruments Types 1 and 3). Two (for 2D anisotropy) or three (for 3D anisotropy) perpendicular *scan lines* are necessary for measurements of the principal thermal conductivity tensor components. No mechanical treatment of any core samples is necessary. Coating the surfaces of the reference standards and the rock samples with a self-adhesive plastic film (easily removed after the measurements) (or with a quick drying enamel paint) is only operation with rock samples before the measurements

require any preparation or mechanical treatment of the crystals beyond that described in this section (Popov et al. 1987).

For measurements on rock fragments and drill cuttings, only fragments with dimensions >8 mm in length and >8 mm in width and >6 mm in thickness should be selected (Table 1). One surface of each fragment must be prepared flat prior to optical scanning.

The thermal conductivity measurements with the optical scanning technique on rock cuttings are possible after the cuttings are mixed with liquids that become solid after mixing as it is described in Sect. 4.6.4.

4.4 Measurement Procedure and Data Processing

Optical scanning instruments are mostly produced commercially and come with an operating manual describing in details the particular measurement procedure to be adhered to.

Before the measurements one or several rock samples should be placed simultaneously on the sample holder provided with the optical scanning instrument as it is shown in Fig. 4. Two reference standards should also be placed on the holder (one at the beginning and one at the end of the scan path) (Fig. 4). The optical scanning instrument manuals include recommendations for appropriate selection of reference standards. Information to identify the samples being measured (for example, region, oil field, well number, depth and other data) is entered into the instrument data acquisition software.

The recommended heater power must be specified. The heater power must provide a sufficient signal-to-noise ratio for excess temperature detection while minimizing the risk of overheating the rock samples. The latter is particularly important for fluid-saturated and thermally sensitive rock samples and for single crystals of rock-forming minerals. Once the heater power is selected, the optical scanning instrument automatically maintains an effective and constant power of the heater during each scan.

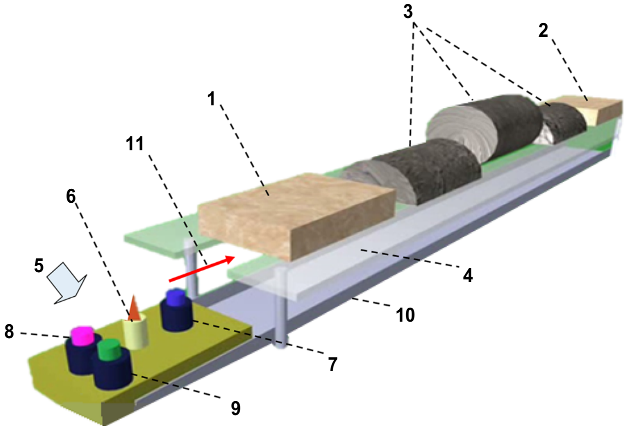


Fig. 4 Scheme of the optical scanning instrument with key components (corresponds to Type 1, Fig. 1). *1* Reference standard 1, *2* reference standard 2, *3* two split core samples and one full size core sample under study, *4* immovable sample holder for core samples and reference standards, *5* optical head with combination of three infrared sensors and optical heat source, *6* optical heat source (electrical lamp for instrument Type 1 and laser for instruments Types 2 and 3 (see Fig. 1), *7* infrared sensor for recording initial temperature level, *8* infrared sensor for thermal conductivity measurements, *9* infrared sensor for thermal diffusivity and volumetric heat capacity measurements, *10* guiding rails for optical head movement under immovable sample holder with reference standards and core samples under study, *11* direction of optical head movement relative to sample holder

The scanning velocity (1–10 mm/s) must be selected based on the thickness of the rock layer under study (Fig. 5). A feature of the optical scanning technique is the ability to investigate different effective thicknesses of the rock layer. Changing the velocity of scanning and/or the distance between the heater spot and the temperature sensors controls the effective thickness of the scanned layer. The effective thickness also depends on the thermal diffusivity of the sample (Fig. 5). The effective width of the rock layer to be studied should be at least twice as large as

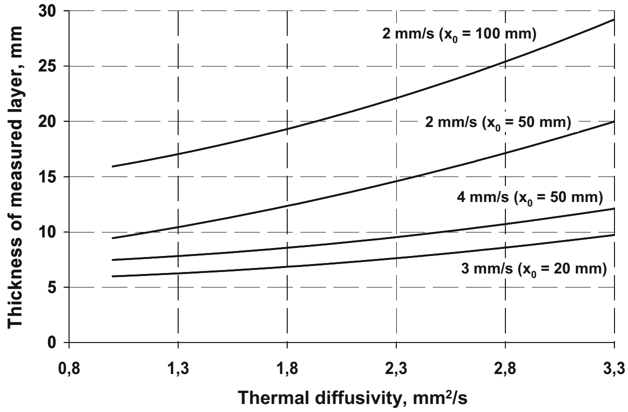


Fig. 5 The effective thickness of a rock sample layer scanned for thermal properties with an optical scanning instrument. Inscriptions for curves indicate different scanning velocities and heater–sensor separations x_0

the effective thickness of that rock layer (see Popov (1984) for more details).

The optical scanning software automatically records thermal properties results for the scan line into an output file after the scanning is completed. The output file contains the following information for the scan: (1) the thermal conductivity and thermal diffusivity (and volumetric heat capacity) profiles recording the distribution of each measured thermal property along the scan line; (2) the average values of the thermal conductivity and thermal diffusivity (and volumetric heat capacity) along the scan line or (optionally) any section of the scan line; (3) the thermal 'heterogeneity factor', *F*, of the scanned rock sample or (optionally) any section of the scan line.

Figure 6 presents an example of the results of thermal conductivity measurements with an optical scanning instrument (Type 3, Fig. 1c). The thermal conductivity distribution is calculated from infrared sensor data using Eq. (5). Local and average values of the thermal conductivity can be determined from the thermal conductivity profile. The three thermal conductivity profiles in the graph show thermal conductivity profiles from three independent scans along the same scan line on the same rock sample; a brecciated rock composed of polygonal fragments of carbonate and quartzite. The three thermal conductivity profiles demonstrate the good repeatability of results from the optical scanning instrument. Therefore, every measurement provides sufficient reliability to warrant a single measurement result and no repeat measurement is required during routine analyses.

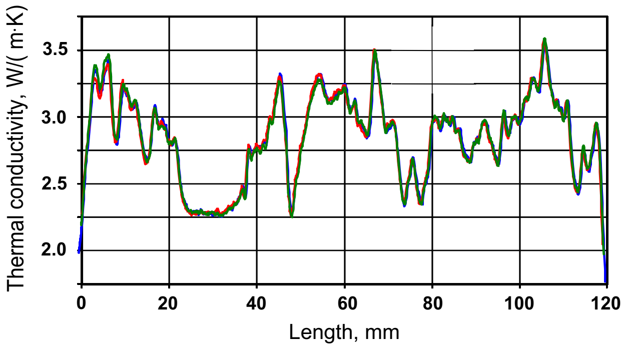


Fig. 6 Thermal conductivity distribution of a brecciated rock sample composed of polygonal fragments of carbonate and quartzite. Three thermal conductivity profiles (shown in *blue*, *red* and *green* and practically coinciding) correspond to three independent scans along the same *scan line* of the same rock sample illustrating the good repeatability of measurements (color figure online)

The thermal heterogeneity of a rock characterizes variability in its texture, structure and composition (Popov et al. 2003a, b). The thermal heterogeneity factor, *F*, of a rock sample is defined as $F = \mathrm{RMSD}/\lambda$, where RMSD is the root-mean-square deviation of the thermal conductivity along the thermal conductivity profile recorded, and λ is the average recorded thermal conductivity value over the same interval. *F* can alternatively be defined as $F = (\lambda_{\max} - \lambda_{\min})/\lambda$, where $\lambda_{\max}$ and $\lambda_{\min}$ are the maximum and minimum values of the thermal conductivity within the recorded profile. A consistent definition of *F* should be adopted across an entire core collection if the value is to be used to differentiate the structure and texture of rock samples.

4.5 Reporting of Results

For each optical scanning scan line, the temperature profiles recorded by infrared sensors 7, 8 and 9 (Fig. 4) are displayed on the computer monitor in real time using the proprietary software supplied with the equipment. Once the scan is completed, the software evaluates the following information for every rock sample in the measurement series: (1) the relative difference, *D*, between the ratio of the thermal conductivity of the two reference standards known from National Standard Bureau certificates or published values, and the observed inverse ratio of the excess temperatures recorded over the reference standards during the measurement. This calculation provides metrological control to the measurement, as indicated by Eq. (3). If the difference in the ratios exceeds a set value, the measurement is considered invalid and should be repeated. (2) thermal conductivity and thermal diffusivity (and volumetric heat capacity) profiles, where the thermal properties values for any given position or section along the scan line, can be queried via the software, (3) information on samples scanned, and key measurement parameters (see Table 2 as an example) are readily recorded. New rows are automatically appended to the current data table. All

Table 2 The standard format for representation of optical scanning measurement results

Name or number of the rock sample	Rock sample No 1	Rock sample No 2	Rock sample No …
Information on region, oil field, well number, measurement date etc. (completed at the start of each rock sample series, and updated)			
Scanning (measurement series) number			
Information about scanning direction (parallel or perpendicular to the core axis) (the information can also be given in the box with rock sample name or number)			
Average thermal conductivity [W/(m K)]			
Maximum thermal conductivity [W/(m K)]			
Minimum thermal conductivity [W/(m K)]			
Average thermal diffusivity (m^2/s)			
Maximum thermal diffusivity (m^2/s)			
Minimum thermal diffusivity (m^2/s)			
Average volumetric heat capacity [J/(m^3 K)]			
Maximum volumetric heat capacity [J/(m^3 K)]			
Minimum volumetric heat capacity [J/(m^3 K)]			
Heterogeneity factor *G*			
Relative difference *D* in ratios of thermal conductivity and temperature values of references			

measurement results for a series can be saved in a local database.

4.6 Notes and Recommendations

4.6.1 Thermal Properties Measurements on Isotropic Heterogeneous Rock Samples

Any direction for a scan line can be chosen for the measurements on isotropic heterogeneous rock samples. To determine thermal properties values for a core sample, the bulk thermal conductivity and thermal diffusivity (and volumetric heat capacity) values can be approximated by averaging the thermal conductivity values determined along a scan lines. The results of multiple measurements along several scan lines and on different surfaces of the same core sample can be averaged for better accounting for rock sample heterogeneity (Popov 1984). Acceptable dimensions of rock samples studied depend on instrument Type (1, 2 or 3) and should be determined according to the information given in Table 1.

4.6.2 Thermal Properties Measurements on Anisotropic Rock Samples

The determination of rock thermal conductivity tensor components is particularly important for characterizing heat transport in anisotropic rock formations. Equation (8) provides the relationship between 'apparent' thermal conductivity (measured thermal conductivity), principal thermal conductivity tensor components, and scan angles. Equation (8) gives a set of three derived Eq. (9) for three apparent thermal conductivity (λ_{app} as per Eq. 8) measurements along three scanning lines oriented parallel to the principal thermal conductivity axes A, B and C (i.e. $\alpha = 90°$, $\beta = 90°$ and $\gamma = 90°$), respectively:

$$\begin{aligned} \lambda_{\mathrm{app1}} &= \sqrt{\lambda_B \lambda_C} \\ \lambda_{\mathrm{app2}} &= \sqrt{\lambda_A \lambda_C} \\ \lambda_{\mathrm{app3}} &= \sqrt{\lambda_A \lambda_B} \end{aligned} \tag{9}$$

Figure 7a illustrates the appropriate scan directions. The three Eqs. (9) have three unknowns, λ_A, λ_B, λ_C, where $\lambda_A \neq \lambda_B \neq \lambda_C$, and can be solved simultaneously.

For 2D anisotropic rock samples, where $\lambda_B = \lambda_C$ and $\lambda_A \neq \lambda_B$, and axis *A* lies parallel to the flat sample surface, the principal thermal conductivity tensor components λ_{II} (along the layering plane) and $\lambda_{\perp}$ (perpendicularly to the layering plane) can be derived from just two scans: parallel and perpendicular to the *A*-axis (Popov and Mandel 1998) as shown on Fig. 7b, c. From the apparent thermal conductivities, λ_{app1} and λ_{app2} determined from these two scans, Eqs. (9) yield:

$$\begin{aligned} \lambda_{\mathrm{app1}} &= \sqrt{\lambda_B \lambda_C} \\ \lambda_{\mathrm{app2}} &= \sqrt{\lambda_A \lambda_C} \end{aligned} \tag{10}$$

and:

$$\begin{aligned} \lambda_{II} &= \lambda_B = \lambda_C = \lambda_{\mathrm{app1}} \\ \lambda_{\perp} &= \lambda_A = \left(\lambda_{\mathrm{app2}}\right)^2 / \lambda_{\mathrm{app1}} \end{aligned} \tag{11}$$

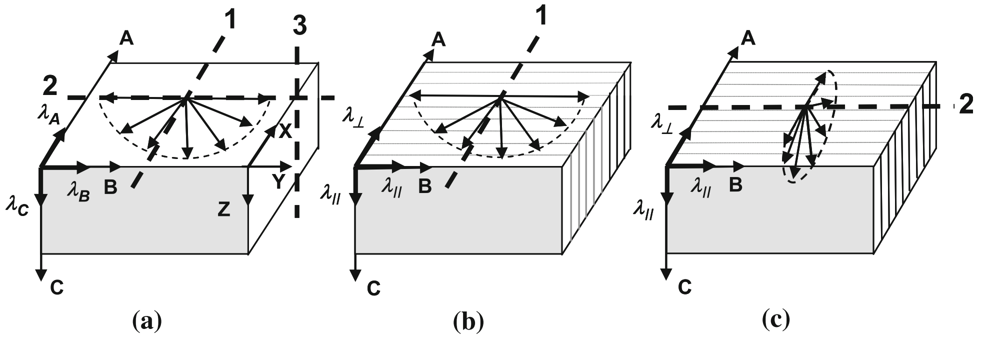


Fig. 7 Scanning directions (*dashed lines*) parallel to the principal axes of thermal conductivity for the determination of principal thermal conductivity tensor components. **a** Three scans (*1*, *2* and *3*) for the general case of a rock sample with 3D anisotropy; **b**, **c** two scans (*1* and *2*) for the case of 2D anisotropy with $\lambda_A = \lambda_\perp$, $\lambda_B = \lambda_C = \lambda_{//}$, $\lambda_{//} \neq \lambda_\perp$. Thin *gray lines* show the bedding planes for rock samples with 2D anisotropy. *Radial arrows* show the plane of heat flow into the rock sample during scanning

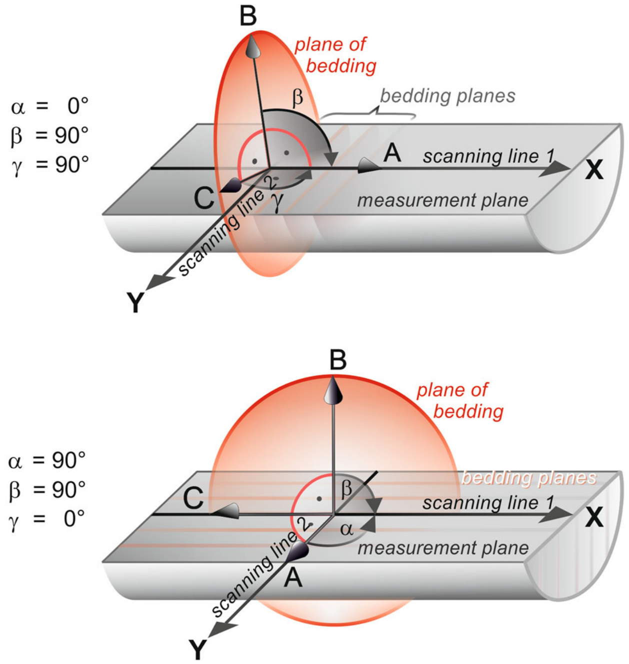


Fig. 8 Scanning directions for measurements of 2D thermal conductivity tensor components on cores with a bedding plane oriented perpendicular to the core axis (*top*) or parallel to the core axis (*bottom*). Axes of coordinate system: *X*, *Y*, *Z*; principal axes of thermal conductivity tensor: *A*, *B*, *C*; angles between coordinate and principle axes: α, β, γ

Figure 8 illustrates how to apply the above in practice for the two simplest cases for core with homogeneous lamination and bedding planes perpendicular or parallel to the core axis. In both cases, thermal conductivity components $\lambda_{//}$ and $\lambda_\perp$ are determined from two perpendicular scans on a single surface of the core.

If anisotropy is suspected but the principal axes of the rock thermal conductivity tensor are unknown, then the principal thermal conductivity tensor components and axes can still be determined. The method requires scanning the same rock surface numerous times, with a rotation of 10°–15° between each scan line (Popov et al. 1999b) (see Sect. 4.8). A similar principle is applied for the line-source technique, as described in Sect. 6.

For a core of layered heterogeneous lithology with transverse isotropic behavior, the bulk values of thermal conductivity along the core axis and perpendicular to the core axis can be determined from a single scan line recorded with temperature sensor 2 (Fig. 2). The bulk thermal conductivity component parallel to the core axis (along the scanning direction) is determined from Eq. (3) using the average excess temperature and represents the geometric mean value of thermal conductivity recorded along the scan line. The bulk thermal conductivity component perpendicular to the core axis and the scanning direction is determined from the arithmetic mean of the recorded conductivity profile (Popov 1984).

4.6.3 *Imaging 2D Heterogeneity and Anisotropy*

Heterogeneity in the thermal properties of a rock is usually due to compositional variations through the rock. This may arise from the irregular distribution of different types of rock fragments or minerals on large or small scales. In contrast, anisotropy is an intrinsic feature of individual crystals that can translate to whole rocks through a dominant alignment of crystals, such as due to pressure or tectonic stress, or because of gravitational or magnetic fields. In other cases, anisotropy can be caused by oriented micro-cracks or porosity of non-spherical pores. Both heterogeneity and anisotropy are scale-dependent. The up-scaled values for whole rock masses and rock sequences are often inferred from measurements on only a few samples. If the number of samples is insufficient to characterize a given rock type, the inferred average thermal properties values may be biased.

Not only borehole-scale studies, but also analyses of basin-scale heat transfer processes generally require assigning single up-scaled values to given rock types. Jorand

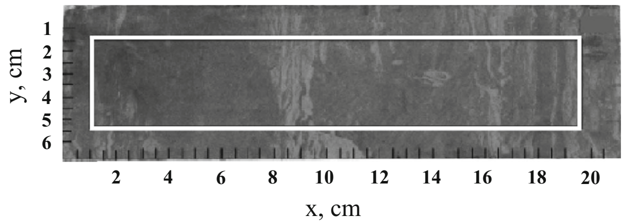


Fig. 9 Photography of the flat surface of the laminated rock sample S1. The white rectangle outlines the area of the scans shown in Figs. 10 and 11 (after Jorand et al. 2013). A color version of the figure is given to show more details in rock sample heterogeneity

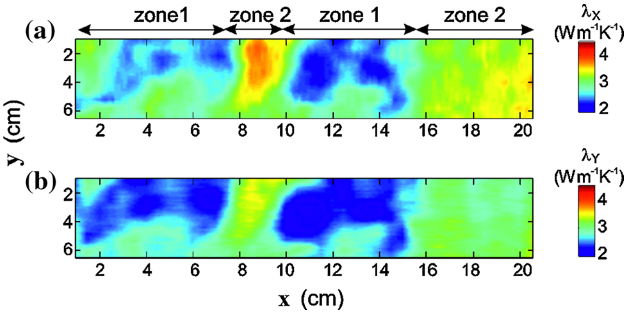


Fig. 10 Surface maps of thermal conductivity of the sample (Fig. 9); **a** in the *X*-direction (along the sample axis) and **b** in the *Y*-direction (perpendicular to the sample axis) showing areas of variable thermal conductivity and anisotropy (Jorand et al. 2013)

et al. (2013) discussed the value of estimating the effective thermal conductivity of heterogeneous and/or anisotropic rock formations based on 2D thermal conductivity imaging. For example, Fig. 9 shows a laminated rock sample, while Fig. 10 shows the associated maps of thermal conductivity when scanned in the *X*- and *Y*-direction; λ_X and λ_Y, respectively. Both heterogeneous and anisotropic conductivities can be identified clearly in these maps. This demonstrates both the importance of capturing the tensor character of thermal conductivity and the difference between an effective (i.e. formation-scale) and a mean thermal conductivity calculated from one of the common mixing laws, such as the geometric or the square-root means (e.g. Clauser 2011). The observed variability can then be taken into account in petrothermal modeling.

From the same rock sample (Fig. 9) and based on their measurements, Jorand et al. (2013) went on to determine the principal thermal conductivity tensor values using relationships of the type given in Eqs. (10) and (11). The corresponding 2D images of the thermal conductivities perpendicular and parallel to the main foliation, $\lambda_\perp$ and $\lambda_{//}$, are shown in Fig. 11a, b, respectively. As expected, thermal conductivity perpendicular to lamination ($\lambda_\perp$) is lower than thermal conductivity within the plane of lamination ($\lambda_{//}$). Figure 11c shows a map of the resulting anisotropy factor, $K = \lambda_{//}/\lambda_\perp$. Lamination anisotropy is characterized by $K > 1$.

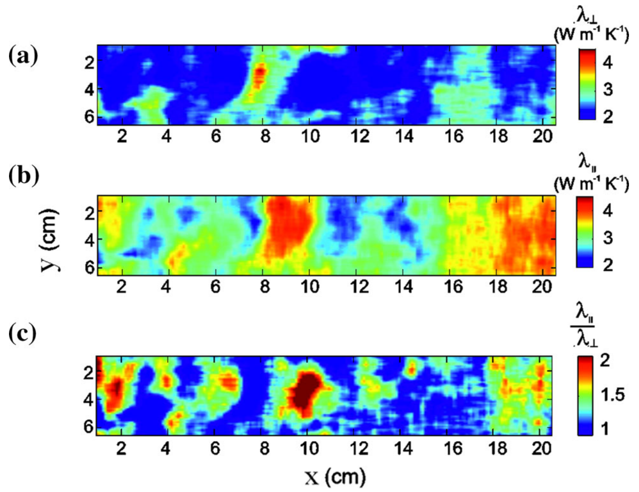


Fig. 11 Images of thermal conductivity of the sample (Fig. 9) in the two main anisotropy directions; **a** $\lambda_\perp$ perpendicular to lamination; **b** $\lambda_{//}$ parallel to lamination; **c** anisotropy factor $K = \lambda_{//}/\lambda_\perp$ (Jorand et al. 2013)

4.6.4 Measurements on Drill Cuttings or Rock Fragments

For thermal conductivity measurements on a sample that is made of drill cuttings or rock fragments, the portion of material available is divided in two parts approximately equal in weight. Two composite samples are prepared from the two parts (drill cuttings) and shaped as disks (typically diameter is 30 mm and height is 20 mm). The composite samples are a mixture of cuttings and a plastic material whose thermal conductivity is known (Popov et al. 2002). It was found that the most suitable plastic materials for this technique are epoxy resin and liquid sodium glass ($\lambda = 0.21$ W/(m K) and $\lambda = 0.97$ W/(m K), respectively) that become solid in 1–2 h. For the composite samples, the size of cuttings varies from 0.06 to 2.5 mm. The cuttings concentration depends on the plastic material used as well as the size and shape of the cuttings. The cuttings concentration ranges from 50 to 60 % in composite samples with epoxy resin and from 30 to 50 % in composite samples filled with liquid sodium glass. When the mixtures become solid, the effective thermal conductivity of each composite sample is measured with the optical scanning instrument. The rock thermal conductivity is found with the help of effective medium theory that provides modeling transport properties of rocks accounting for the rock particle shapes, their orientation, and distribution in space (Bayuk et al. 2011). The thermal conductivity measurement uncertainty was found to be within 3–8 % in relation to a measurement on the same core before destruction. The average uncertainty of the proposed technique was found to be ±6 % (Popov et al. 2002).

4.7 Limitations and Common Sources of Error

All samples must meet the minimum thickness, length and width requirements given in Table 1 to ensure that scanning results do not underestimate the true thermal properties of the samples. Samples should be arranged on the optical scanning instrument such that scan lines are set sufficiently away from any sample boundary, according to Table 1 and depending on rock thermal conductivity value (Popov et al. 1993). Boundary effects can impact on the accuracy of results near the edge of a sample (5–10 mm) along a scanning line.

Thermal conductivity is most accurately measured if it differs by less than a factor of two (smaller or larger) from the thermal conductivity of either of the two reference standards. Thermal diffusivity is most accurately measured if its value lies between the thermal diffusivities of the two reference standards. This highlights the importance of carefully choosing the reference standards for the expected range of thermal properties values to be measured.

If measurements are performed on the cylindrical surface of core samples with a core diameter of less than 80 mm and/or the thermal conductivity exceeds 5 W/(m K), then a systematic error can be estimated and accounted for in all measurements. A correction factor must be then determined by comparing results obtained from measuring for the same core, flat versus cylindrical surfaces, and this across several core samples.

4.8 Metrological Considerations

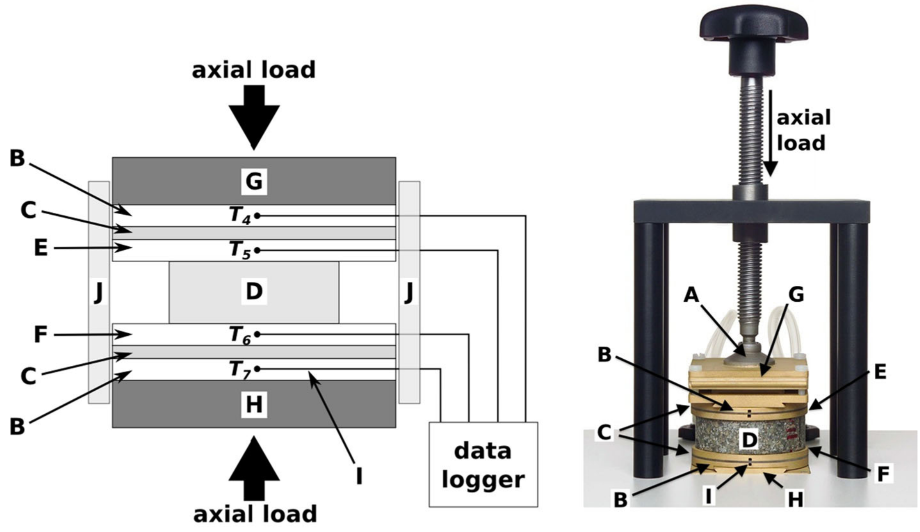
One level of metrological control is automatically included during every optical scanning measurement using the ratio of excess temperatures observed over the two reference standards compared to the inverse ratio of their thermal conductivities, according to Eq. (3). This procedure allows, first, to detect, reduce and exclude occasional errors caused by possible accidental instabilities in heater power, scanning velocity, electronic problems, and second, to demonstrate consistency in the quality of the measurement.

Periodically placing one or several additional reference standards between the other two recommended reference standards provides a mean to additional metrological testing of the optical scanning instruments. After such an experiment is repeated sufficiently for robust statistical confidence, the thermal conductivity and thermal diffusivity measurement results should be collated and compared with published thermal properties values of the reference standards. The variance in random error within the results allows for the estimation of measurement precision.

The adequacy of experimental and theoretical models of optical scanning measurements for anisotropic samples can be confirmed through measurements on single quartz crystals, which have well-known thermal conductivity values of $\lambda_A = \lambda_B = 6.05 \pm 0.05$ W/(m K) for the crystallographic A and B axes and $\lambda_C = 10.7 \pm 0.1$ W/(m K) for the C-axis at room temperature (Beck 1987; Popov et al. 1990). Several measurements at each of a number of angles with respect to the conductivity axes are recommended.

At least two possible challenges could be met with in practice:

1. There is uncertainty over whether the principal axes of rock thermal conductivity can be determined correctly (Mottaghy et al. 2005);



(a) (b)

Fig. 12 Scheme (**a**) and photography (**b**) of a divided-bar apparatus. A Pivot point, B brass disks, C reference material, D rock specimen, E hot plate, F cold plate, G heat source (concealed Peltier device), H heat sink (concealed Peltier device), I holes for the insertion of temperature sensors, J thermal insulation

2. There is uncertainty about whether samples are isotropic or anisotropic.

Several scans on each of one, two or three non-parallel surfaces (depending on the particular case) will almost always provide certainty for each of the above situations.

More detailed recommendations for optical scanning metrological testing and control are included in Sect. 7.

5 Divided-Bar Technique

The steady state divided-bar technique is arguably the most widely used method for rock thermal conductivity measurements, in view of its simplicity of design, construction and operation. The most commonly used divided-bar units in geothermal laboratories today employ the same working principle as the device described by Birch (1950).

5.1 Experimental Setup

A divided-bar instrument consists of the following key elements as is illustrated in Fig. 12.

1. A heat source and a heat sink maintain constant temperatures (±0.03 °C) at each end of the stack. The heat source is typically about 20 °C warmer than the heat sink, with the mean temperature 5–10 °C above ambient. Possible heating/cooling devices include thermostatically controlled water baths, electrical heating coils, and Peltier devices.
2. A hot plate and a cold plate of high thermally conductive material (brass, aluminum or copper) make direct thermal contact with the rock specimen via flat and smooth faces, and hold embedded temperature sensors.
3. Two disks of isothermal material (brass, aluminum or copper) efficiently transfer heat from the heat source to the upper reference material, and from the lower reference material to the heat sink, and hold embedded temperature sensors.
4. Two disks of reference material (typically 'Lexan' polycarbonate) provide constant thermal resistances against which the thermal resistance of the rock specimen is compared.

These components must be firmly bonded together into upper and lower assemblies for the lifetime of the divided-bar instrument. A divided-bar instrument should also incorporate the following.

1. A means to apply pressure not exceeding 100 kPa (1.0 bar) normal to the plane of thermal contact between the hot/cold plates and the rock specimen to ensure good thermal contact during a measurement. An optimal design includes a pivot point to allow alignment of the plates to specimen faces not precisely parallel.
2. Four temperature sensors (thermocouples or small bead thermistors, indicated as T_4, T_5, T_6 and T_7 on Fig. 12) positioned within the hot plate, cold plate and isothermal material components as near as possible to the central axis of the bar. They should provide temperature data to a precision of ±0.001 °C and an accuracy of 0.01 °C in order to ensure divided-bar instrument accuracy of ±2 % at the upper end of the conductivity measurement range.
3. A data logger to capture the temperature data from the sensors. Digital logging units compatible with a wide range of temperature sensors are readily commercially available.
4. Practical experience has shown that it is critical to stifle the circulation of air past the rock specimen to ensure axial heat flow and to avoid radial heat flow during a measurement. A cushion of air at the mean measurement temperature around the specimen provides efficient thermal insulation to maximize axial heat flow and minimize radial heat flow. Such an air cushion can be achieved by enclosing the assembly in airtight foam material during the measurement.

Practical devices for measurements of rock specimens should accommodate common drill core diameters to maximize the efficiency of specimen preparation from core. Common core diameters include 27.0 mm (AQ), 36.5 mm (BQ), 43.5 mm (CHD76), 47.6 mm (NQ), 63.5 mm (HQ/CHD101) and 85.0 mm (PQ/CHD134). A divided-bar instrument with a bar diameter of 65 mm provides a good compromise between core accommodation and the ability to evenly heat/cool the hot/cold plates. Prismatic specimens other than disks should be prepared to fit wholly within the bar perimeter. Pre-assembled divided-bar units that have undergone a rigorous design and testing process are available from commercial suppliers. Figure 12 includes an example divided-bar apparatus with some of the key components labeled.

Effective operation of a divided-bar instrument also requires ancillary equipment including (1) a set of calibration reference standards covering a range of thermal resistances, (2) hollow cells to hold unconsolidated or weak rock specimens, (3) a micrometer to measure the dimensions of the rock specimens, (4) rock saw, grinding and polishing equipment.

Equipment must be sufficient to prepare specimens to the same standards as recommended in the ISRM suggested methods paper for determining the uniaxial compressive strength and deformability of rock materials

Table 3 Technical parameters for a typical divided-bar apparatus

Parameter	Value
Diameter of bar (mm)	25–65
Diameter of specimen (mm)	25–65 (limited by bar diameter)
Thickness of specimen (mm)	10–30
Conductivity range [W/(m K)]	1.0–10.0
Accuracy (%)	±2 (core), ±10 (cuttings)
Precision (%)	±1 (core), ±3 (cuttings)
Warm-up time (h)	1
Measurement rate	2 Specimens per h
Maximum sampling resolution	1 Specimen per 30 mm
Measurement temperature range	Ambient ±10 °C

(Bieniawski and Bernede 1979), namely (a) the ends of the specimen shall be flat to 0.02 mm and shall not depart from perpendicularity to the axis of the specimen by more than 0.001 rad (about 3.5 min) or 0.05 mm in 50 mm; (b) The sides of the specimen shall be smooth and free of abrupt irregularities and straight to within 0.3 mm over the full length of the specimen; (c) The use of capping materials other than those listed in Sect. 5.5 or end surface treatments other than machining is not permitted; (d) The diameter of a cylindrical test specimen shall be measured to the nearest 0.1 mm by averaging two diameters measured at right angles to each other at about the upper-height, the mid-height and the lower height of the specimen. The average diameter shall be used for calculating the cross-sectional area. (e) The thickness of the specimen shall be determined to the nearest 0.05 mm.

Table 3 summarizes the important technical parameters of a typical divided-bar apparatus.

5.2 Theoretical Background

The divided-bar technique provides the conditions to compare the thermal resistance of a rock specimen, R_{rock}, to that of a reference material, R_{ref}. A prismatic rock specimen is placed in series between two identical disks of the reference material, and a constant temperature differential is applied across the stack. The heat flowing through the stack has to pass through the reference material and the rock specimen (as well as any contact resistances). At steady state, and assuming uniaxial heat flow through the stack, heat flow (q) across the reference material is the same as that across the rock specimen and the contact faces:

$$q_{\text{ref}} = q_{\text{rock+contact}} \tag{12}$$

Substitution in (12) of $q = \Delta T/R$, where $\Delta T/R$ is the change in temperature ΔT across a thermal resistance R, gives us:

$$\left(\frac{\Delta T}{R}\right)_{\text{ref}} = \left(\frac{\Delta T}{R}\right)_{\text{rock+contact}} \tag{13}$$

The thermal resistance of the rock specimen is, therefore, given by the linear relationship:

$$R_{\text{rock}} = R_{\text{ref}}\frac{\Delta T_{\text{rock+contact}}}{\Delta T_{\text{ref}}} - R_{\text{contact}} \tag{14}$$

where R_{contact} is the total contact resistance between the rock specimen and the hot/cold plates.

After calibrating a divided-bar apparatus to determine R_{ref} and R_{contact} (see Sect. 5.3), the thermal resistance of a rock specimen can be determined precisely by measuring the temperature drops across the two reference disks and across the rock specimen and contact faces at steady state. The thermal conductivity of the rock specimen, λ_{rock}, is then:

$$\lambda_{\text{rock}} = \frac{l_{\text{rock}}}{R_{\text{rock}}} \tag{15}$$

where l_{rock} is the thickness of the rock specimen.

5.3 Calibration Procedure

Referring to Eq. (14) and Fig. 12, $\Delta T_{\text{rock+contact}}$ is equal to the temperature drop (T_5–T_6), and ΔT_{ref} is equal to the total temperature drop across the two disks of reference material, [(T_4–T_5) + (T_6–T_7)]. Equation (14) can therefore be re-written in terms of temperatures measured in the divided-bar apparatus at steady state:

$$R_{\text{rock}} = R_{\text{ref}}\frac{T_5 - T_6}{T_4 - T_5 + T_6 - T_7} - R_{\text{contact}} \tag{16}$$

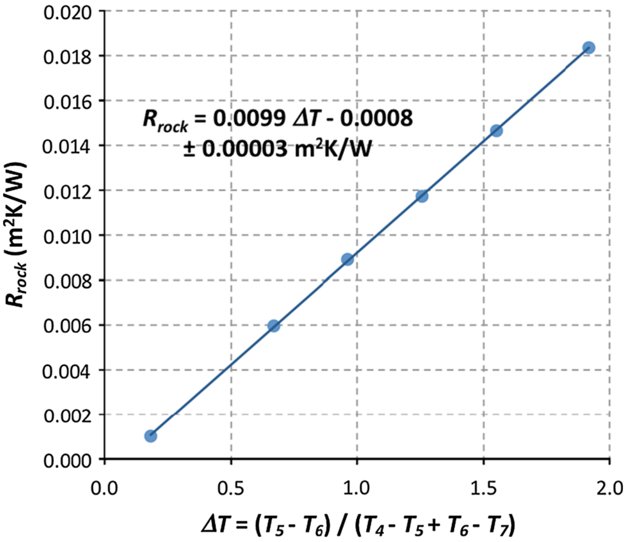


Fig. 13 Example of a calibration plot for a divided-bar apparatus

If, instead of rock specimens, a set of calibration reference standards covering a range of known thermal resistances is measured, the linear relationship between the known resistances and the ratio of the temperatures at steady state can be derived, and hence the coefficients R_{ref} and R_{contact}. Figure 13 shows an example using six reference standards to derive the calibration constants for a divided-bar instrument. In this example $R_{\text{ref}} = 0.0099$ m^2 K/W and $R_{\text{contact}} = 0.0008$ m^2 K/W, and the scatter gives an uncertainty of ± 0.00003 m^2 K/W for subsequent derived values of R_{rock}.

If specimens of arbitrary surface area are to be measured, then the divided-bar apparatus should be calibrated using reference standards covering a range of surface areas. R_{ref} and R_{contact} can then be defined as functions of surface area.

5.4 Specimen Preparation

Three specimens from each rock sample should be prepared and measured if enough material is available, to provide a simple estimate of variance and improve the overall confidence of the results.

5.4.1 Competent Rocks

Rock specimens are usually prepared as prisms with flat, polished, sub-parallel top and bottom faces. The maximum surface area of the prism top/bottom face is limited by the diameter of the bar of the divided-bar apparatus. The prism should be of a thickness to make its thermal resistance close to R_{ref} in order to place it close to the middle of the divided-bar apparatus calibration range ($\Delta T \sim 1.0$ in Fig. 13). Furthermore, the specimen should be sufficiently thick to represent the bulk rock but not so thick that radial heat transfer becomes significant. A thickness of about one half the sample diameter is recommended. Within these constraints, specimens commonly range from 10 to 30 mm thick. It is usual practice to simulate the in situ condition of the rock by fully saturating each specimen with water, but specimens can also be measured dry or partially saturated.

Heat conduction has strong parallels with sound transmission through a rock (Beardsmore and Cull 2001). Specimen preparation for divided-bar measurements should, therefore, follow a similar method as for sound transmission measurements such as described by Aydin (2014). Specifically, the divided-bar method requires test specimens with smooth (using fine grit), flat (maximum gap size between specimen surface and standard straight-edge accommodates <0.025 mm thick feeler gage) and parallel (<0.01/10 mm of specimen diameter) faces. The thickness of the specimen shall be determined to the nearest 0.05 mm. The diameter of a cylindrical specimen shall be measured consistent with the ISRM suggested methods for Determining the Uniaxial Compressive Strength and Deformability of Rock Materials (Bieniawski and Bernede 1979). Namely, to the nearest 0.1 mm by averaging two diameters measured at right angles to each other at about the upper-height, the mid-height and the lower height of the specimen. The average diameter shall be used for calculating the cross-sectional area.

5.4.2 Unconsolidated Rocks

Sass et al. (1971) developed a method for measuring the conductivity of weakly consolidated rocks and unconsolidated rock fragments using a divided-bar unit. The rock material is packed into a specially constructed cell of a design and dimensions similar to those shown on Fig. 14 and saturated with water before closing the lid of the cell. Weakly consolidated rocks should be carefully trimmed to fit snugly within the cell dimensions while maintaining their competence. Unconsolidated rock fragments should be packed tightly into the cell. The base and the lid of the cell have high thermal conductivity values (copper, brass or aluminum), while the walls are thin and have low thermal conductivity values (polycarbonate ‘Lexan’, ‘Perspex’ or other plastic). The thermal conductivity of the packed and saturated cell is measured as described in Sect. 5.5. Subsequent mathematical treatment of the data, also described in Sect. 5.5, removes the thermal effect of the cell to derive the thermal conductivity of the rock material.

5.5 Measurement Procedure and Data Processing

The laboratory should be free from draughts and rapid temperature fluctuations during the testing. An operator should turn on the divided-bar apparatus at least 1 h ahead of time so that it reaches stable operating temperatures before the measurement commences. It is necessary after that: (1) to measure the thickness through the center of the

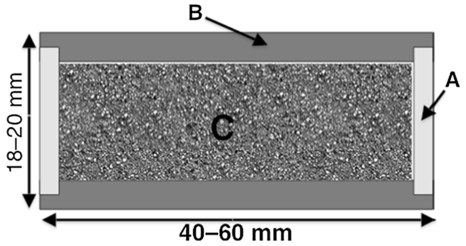


Fig. 14 Typical dimensions of a cell for measuring thermal conductivity of rock fragments in a divided-bar apparatus. *A* Polycarbonate wall ~2 mm thick, *B* brass or copper ~3 mm thick, *C* unconsolidated rock or rock fragments saturated with water (after Sass et al. 1971)

specimen to a precision of 0.01 mm and an accuracy of 0.05 mm, to keep the overall measurement error minimal, (2) to remove any surface water from the specimen, and (3) to smear both polished faces of the specimen with petroleum jelly, or similar benign water and air resistant substance, to ensure an airtight contact between the specimen and the hot/cold plates. A thin film of the same substance can be applied to the walls of porous specimens to retard evaporative water loss during measurement, taking care not to force the substance significantly into the pores.

Next steps are as follows: (1) to align the center of mass of the specimen as closely as possible to the middle of the cold plate and displace all air from between the specimen and the plate, and (2) to bring the two halves of the divided-bar apparatus together to hold the specimen securely between them. It is recommended to limit the applied load as this can mechanically damage the specimen and alter its thermal conductivity. It is recommended that the axial stress on a competent specimen not exceed 100 kPa (1.0 bar), and less for weaker specimens. Insulation should then be applied around the specimen.

Temperatures T_4, T_5, T_6 and T_7 should be monitored until a steady state is reached. This typically takes between 5 and 20 min, depending on the heat capacity of the specimen. The four stabilized temperatures should be recorded to at least four significant digits.

After the measurements it is necessary (1) to remove the insulation and release the axial load gradually while applying a gentle twisting motion to the specimen in the horizontal plane, (2) remove the specimen from the divided-bar apparatus, (3) clean the hot/cold plates immediately with a clean moist towel, and (4) to measure the cross-sectional area of the specimen. The measurement procedure is now complete, and the divided-bar apparatus is ready for the next specimen measurement.

An experienced divided-bar apparatus operator should be able to complete at least two measurements per h, after the initial 1-h instrument warm-up time.

To process the data, the calibration coefficients, R_{ref} and R_{contact}, should be determined for the surface area of the specimen. The operator should input these and the measured steady state values of T_4, T_5, T_6 and T_7 into Eq. (16) to calculate R_{rock} and apply Eq. (15) to derive the thermal conductivity of the specimen from R_{rock} and the specimen thickness (or internal height of a closed hollow cell). This is all that is required for consolidated rock specimens. Careful calibration and measurement processes should provide precision on the order of ±1 %, and accuracy of about ±2 %.

For specimens measured in hollow cells, the thermal conductivity of the core or water/rock mixture within the cell, λ_{mix}, can be derived:

$$\lambda_{\mathrm{mix}} = (\lambda_{\mathrm{bulk}} - \lambda_{\mathrm{cell}})\, A_{\mathrm{cell}}/A_{\mathrm{mix}} \tag{17}$$

where λ_{bulk} is the measured thermal conductivity of the full cell, λ_{cell} is the measured thermal conductivity of the cell when empty, A_{cell} is the total surface area of the full cell, A_{mix} is the surface area of the interior of the cell occupied by the water/rock mixture. For weak but otherwise competent core, λ_{mix} is the conductivity of the saturated core.

The mean thermal conductivity of randomly orientated rock fragments in a mixture, λ_{rock}, can be approximated by either the square-root mean (Beardsmore and Cull 2001):

$$\lambda_{\mathrm{rock}} = \left(\frac{\sqrt{\lambda_{\mathrm{mix}}} - S\sqrt{\lambda_{\mathrm{water}}}}{1 - S} \right)^2 \tag{18}$$

or the geometric mean:

$$\log_n(\lambda_{\mathrm{rock}}) = [\log_n(\lambda_{\mathrm{mix}}) - S \log_n(\lambda_{\mathrm{water}})]/(1 - S) \tag{19}$$

where λ_{water} is thermal conductivity of water at the measurement temperature, and S is the 'saturation', or proportion of water in the mixture ($0 < S < 1$).

For cell measurements, precision is on the order of ±3 %, and accuracy is on the order of ±10 %.

5.6 Reporting of Results

Table 4 lists relevant data to include in a report of thermal conductivity measurements made with a divided-bar apparatus.

5.7 Notes and Recommendations for Measurements on Anisotropic Rock Samples

The 3D thermal conductivity tensor, with determination of principal tensor components, is sometimes required. Popov and Mandel (1998) and Popov et al. (1999b) described the relationship between thermal conductivity measured with a divided-bar apparatus, λ_{rock}, and the principal thermal conductivity axes of anisotropic rocks where the divided-bar axis is at an angle, ω, to the normal to the specimen's dominant foliation or bedding:

$$\lambda_{\mathrm{rock}} = \sqrt{\lambda_{\perp}^2 \cos^2 \omega + \lambda_{\mathrm{II}}^2 \sin^2 \omega} \tag{20}$$

where $\lambda_{\perp}$ and λ_{II} are the principal thermal conductivity tensor components perpendicular and parallel, respectively, to the dominant foliation.

Antriasian (2010) described the preparation of a rectangular prism for anisotropy analysis, with all six faces polished for contact with the divided-bar components. One axis of the prism should be orientated normal to the dominant foliation or bedding plane, and the other axes aligned parallel and perpendicular to any apparent lineation

Table 4 Recommended data to include in a thermal conductivity report

Sample description	Specimen preparation	Measurement conditions	Results
Sample ID number	Number of specimens prepared from the sample	Mean measurement temperature	Calculated thermal conductivity of each specimen
Well or borehole name	Flatness and smoothness of specimen surfaces	Temperature differential across divided-bar	Uncertainty range for each specimen
Location coordinates	Consolidated specimen/hollow cell measurement		Harmonic mean and standard deviation of multiple specimens from same sample
Sample depth	Water saturation process		Discussion of any noteworthy or outlier results
Formation name	Specimen diameter/surface area		
Lithological description	Specimen thickness		
Core/cuttings/hand sample	Specimen mass (wet and/or dry)		
Sample photograph			

within the dominant foliation. Three individual conductivity measurements are then completed along the three orthogonal axes. Alternatively, three individual specimens can be prepared and measured from the same sample, with measurement axes parallel to the three expected principal tensor axes.

5.8 Limitations and Common Sources of Error

Specimen preparation is time-consuming and can affect the accuracy of the measurement. Accuracy is also impacted by the strength and texture of the specimen. Weak rocks (including those that lose strength upon saturation) can only support a small axial load, which can influence the thermal resistance between the specimen and the hot/cold plates, and also the accuracy with which surface area and thickness can be measured. This can be of particular concern in tropical countries with high humidity. Furthermore, sampling resolution is limited to several centimeters. Measurements over smaller or larger thicknesses are generally not practical. Imperfections in specimen flatness and polish can increase the surface contact resistance far in excess of the calibration coefficient, R_{contact}. Small air pockets at the plate faces result in an erroneously low ‘measured’ thermal conductivity values for the specimen.

5.9 Metrological Considerations

Recommendations for divided-bar apparatus metrological testing and control are the same as for other thermal conductivity measurement methods. Section 7 describes these in detail.

6 The Line-Source Technique

The line-source technique had intensive implementation in the 1980s and 1990s when it was adopted by the United States Geological Survey (USGS), German Research Centre for Geosciences (GFZ), Potsdam, Leibniz Institute for Applied Geophysics (LIAG), Hannover and the Technical University of Berlin (TU Berlin) for geothermal research and by the KTB laboratory (Germany) for thermal conductivity measurements on more than 600 core samples from the super-deep scientific KTB well (Germany).

6.1 Experimental Setup and Technical Parameters

The line-source technique allows measurement of the thermal conductivity on different rock samples featuring a flat surface. The most typical and convenient line-source technique is a half-space line-source one where a needle probe is embedded into the bottom side of a disk of a material with very low thermal conductivity (e.g. Plexiglass). The half-space probe should be placed on a flat surface of the rock sample. During the measurements, the probe disk with the embedded line-source has a one-sided contact with the rock sample. Details of the construction and a special evaluation algorithm are described in Huenges et al. (1990) and in the manual of the TK04 Thermal Conductivity Meter instrument produced by TeKa (http://www.te-ka.de) (Fig. 15). Another version of a probe is the full-space line-source probe designed to measure weak or weakly consolidated material.

It was shown that the requirement of an infinite probe length is sufficiently satisfied if the length-to-diameter ratio of the needle probe exceeds 30:1 and if the probe temperature is recorded at the center of the probe (Blackwell 1954).

The technical parameters of the commercially available line-source instrument, the TK04 Thermal Conductivity Meter, are shown in Table 5. The instrument has different probe types that correspond to different rock sample types and different measuring conditions. The full-space line-source probe is constructed as a needle that is inserted directly into the sample. The half-space probe is constructed as a needle-bearing disk that is placed on the flat surface of a rock sample. There are two types of half-space probes: (1) the standard half-space probe that should be used for measurements on rock samples with a minimum dimension no less than 80 mm, and (2) the mini half-space probe that can be used for measurements on rock samples with a minimum dimension no less than 50 mm.

Characteristics of the TK04 Thermal Conductivity Meter are that (1) thermal conductivity measurements can be performed on a flat cross section of full size core, (2) thermal conductivity measurements can be performed on a flat surface of split core, (3) principal values of the thermal conductivity tensor components can be determined from measurements on one or two flat surfaces of the core sample, and (4) sample temperature during measurement may range from −25 to 125 °C.

Details of the construction and a special evaluation algorithm are described in Huenges et al. (1990) and in TeKa (2014).

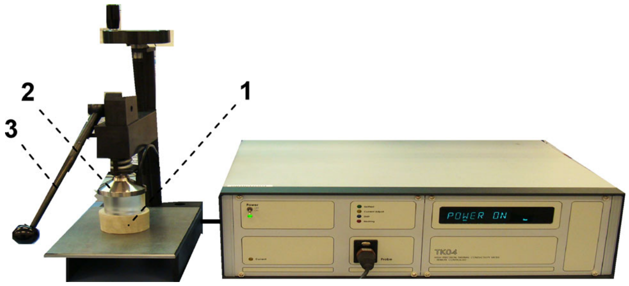


Fig. 15 The TK04 thermal conductivity meter instrument and core sample holder with the half-space probe applied to cylindrical rock sample. *1* Rock sample under study, *2* measuring half-space probe, *3* arrangement to press measuring half-space probe to rock sample surface

6.2 Theoretical Background

The line-source method is based on heating a rock sample with a thin wire (the 'line-source') where simultaneously the temperature of the wire is measured. At the onset of heating, variation of the wire temperature is described by the equation (Blackwell 1954; Carslaw and Jaeger 1959):

$$\lambda = \frac{q'}{4\pi} \cdot \frac{\ln\left(\frac{t_2}{t_1}\right)}{T(t_2) - T(t_1)} \tag{21}$$

where λ is the thermal conductivity of the rock sample under study (the sample is considered a 'full-space' volume as the line-source is an 'infinite medium'), q' is the power of the line-source per length unit, t_1 and t_2 are times at which line-source temperatures $T(t_1)$ and $T(t_2)$ are measured.

According to Grubbe et al. (1983), the 'apparent' thermal conductivity obtained from the measurement of

Table 5 Technical parameters of the instrument TK04 thermal conductivity meter (TK04 Manual, 2014)

Parameter	Full-space line-source probe	Half-space line-source probe	
		Standard	Mini
Measuring range [W/(m K)]	0.1–10	0.3–10	0.3–3
Accuracy (%)	2	2	5
Duration of 1 measurement (s)	80	80	60
Recommended time interval between measurements on two samples (min) (s)	30	30	30
Line-source dimensions			
Length (mm)	70	70	45
Diameter (mm)	2	2	1.5
Probe dimensions			
Diameter (min) (mm)	30	88	50
Height (min) (mm)	75	30	30
Rock sample dimensions (min)* (mm)			
Diameter (mm)	Approx. 30	Approx. 80	Approx. 50
Height (mm)	75	Approx. 15	Approx. 15

* Larger sample thicknesses may be required for measurements on materials with higher thermal conductivities

an anisotropic sample is related to the principal components of the thermal conductivity tensor according to the equation:

$$\lambda_{\mathrm{app}} = \sqrt{\lambda_A \lambda_B \cos^2 \gamma + \lambda_A \lambda_C \cos^2 \beta + \lambda_B \lambda_C \cos^2 \alpha} \qquad (22)$$

where α, β and γ are angles between the line-source axis and principal axes of thermal conductivity A, B, and C, respectively.

It is noteworthy that Eq. (22) elaborated by Grubbe et al. (1983) for the line-source method coincides with Eq. (8) elaborated by Popov and Mandel (1998) for the optical scanning technique; while the situations are similar geometrically they are quite different physically. As follows from Eq. (22), the principal thermal conductivity tensor components can be determined by three non-collinear and non-coplanar line-source measurements, thus defining angles α, β and γ. It is intuitive that accurate measurements are provided by a consecutive arrangement of the line-source probe along each principal axis of thermal conductivity.

For 2D anisotropic rock samples (where $\lambda_A = \lambda_B = \lambda_{II}$ and $\lambda_C = \lambda_{\perp}$) and to mitigate uncertainty in estimating the principal axes from visual inspection alone, the line-source probe can be placed on the top plane of the core (perpendicular to the core axis) and 'apparent' thermal conductivity can be measured with varying line-source probe azimuth (Fig. 16) (see also Pribnow and Sass 1995). Considering that the thermal conductivity parallel to the foliation is higher than the thermal conductivity perpendicular to the foliation, the strike of the foliation is assessed by the position of the line-source returning the lowest thermal conductivity value. The core can be then cut parallel to its axis and perpendicular to the estimated strike of foliation (Fig. 16), where thermal conductivity can be measured at varying line-source probe angles in order to characterize the thermal conductivity tensor. The maximum thermal conductivity measured value represents λ_{II}. For measurements perpendicular to the foliation, the minimum thermal conductivity measured value is as λ_{min}. Following Eq. (22), if λ_{II} is known (and $\alpha = \beta = 90°$; $\gamma = 0°$) $\lambda_{\perp}$ can be determined using:

$$\lambda_{\mathrm{min}} = \sqrt{\lambda_{\mathrm{II}} \lambda_{\perp}} \qquad (23)$$

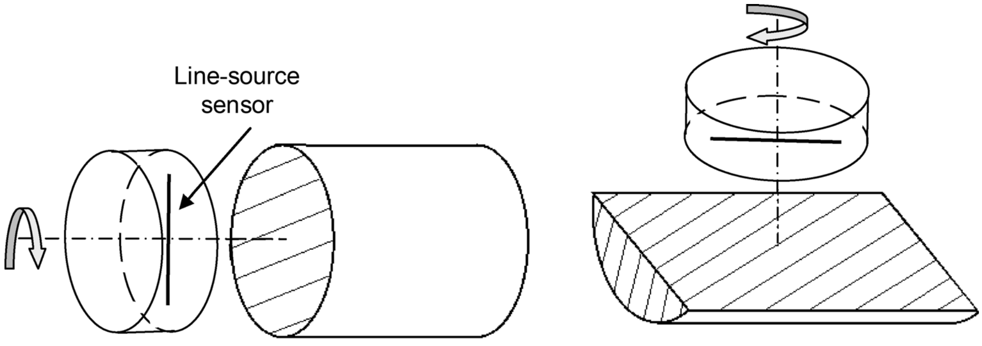
6.3 Specimen Preparation

Thermal conductivity measurements with the TK04 half-space probe can be performed if a rock sample has a plane and smooth surface. The preparation of such surface can be done carefully by grinding and/or polishing the sample to achieve optimal thermal contact between the half-space probe and the rock sample. The rock sample diameter should be no smaller than shown in Table 5 and is dependent on the probe diameter. The thickness of the rock sample should be no less than 15 mm.

The application of a contact paste is recommended between the line-source probe surface and the rock sample surface to provide optimal thermal contact. If the contact paste penetrates into a porous rock sample, the measured thermal conductivity value will differ from the natural thermal conductivity of the rock sample. Therefore, highly viscous contact liquids are recommended as candidates for a suitable contact paste. The contact liquid should be used that is appended to the TK04 instrument by the instrument producer TeKa company or it should be chosen according to the recommendations from the TeKa. To provide for optimal thermal contact between the half-space probe and the rock sample, a moderate pressure of 500–1000 kPa (5–10 bar) should be applied to the half-space LS probe and the sample surface assembly. This can be achieved with the sample holder supplied by the manufacturer (see Fig. 15).

6.4 Measurement Procedure and Data Processing

A series of line-source measurements can be performed to characterize the thermal conductivity heterogeneity of a rock sample and establish a thermal conductivity profile.



(a) (b)

Fig. 16 Assessing thermal conductivity anisotropy of a rock sample with the line-source technique. **a** Measurement on a flat cross section of a core sample, **b** measurement on flat surface of a split core

This can be achieved effectively by shifting the line-source probe 5–8 mm, after every measurement, along the direction of the line-source needle axis or parallel to the core sample axis. Multiple measurements with the line-source instrument via a probe shifting technique can be useful to assess the thermal conductivity of heterogeneous rocks. Multiple thermal conductivity measurements, and subsequent averaging, on different parts of the core studied yield increased statistical confidence in thermal conductivity measurements thus providing robust estimates of bulk thermal conductivity.

For 3D anisotropic rock samples, the principal values of the thermal conductivity tensor can be determined from a set of three equations by using Eq. (22) and by taking three line-source measurements of non-collinear and non-coplanar directions on two non-parallel planes of the rock sample. For a rock sample with 2D anisotropy, the principal values of the thermal conductivity tensor can be determined from two line-source measurements of non-collinear direction on one face of the rock sample, as long as this face is not parallel to the foliation of the rock sample.

If the rock sample thickness is about 15 mm, or less, there is a risk of additional systematic error in the thermal conductivity measurement results. To reduce this risk, the TK04 manufacturer recommends the use of a lower heating power and/or to increase pauses, up to 30 min, between single measurements from the standard minimum value of 10 min.

Finally for all measurements, it is recommended to place the rock sample and the line-source probe in a thermally insulated container to prevent external temperature changes affecting the measurement process.

6.5 Reporting of Results

Thermal conductivity measurement results and measurement regime parameters are set and saved automatically to a computer file via proprietary software supplied by the manufacturer. Every thermal conductivity measurement produces a recorded log of transient temperatures with respect to time. Upon completion of a series of measurement, the results can be evaluated and analyzed in detail (TeKa 2014).

To improve thermal conductivity measurement quality, it is recommended to set a constant heating power as well as a constant time pause between two typical thermal conductivity measurements. It is also recommended that the rock sample thickness and dimensions of the rock sample surface to be measured remain similar across the rock sample collection for the experiment.

In assessing the thermal conductivity tensor for anisotropic samples, it is necessary to set defined angles between the axis of the line-source needle and the principal thermal conductivity axes. The level of confidence in determining the principal axes of thermal conductivity can also be reported along with the corresponding thermal conductivity measured values (i.e. mean values) and their uncertainty (i.e. standard deviations). Once the thermal conductivity tensor is calculated from primary measurements according to recommendations outlined in Sect. 6.2, further calculated results (λ_{app}, $\lambda_{\min}$, $\lambda_{//}$, $\lambda_{\perp}$) can be reported.

6.6 Notes and Recommendations

Another line-source instrument application is the full-space needle probe inserted into the rock sample (e.g. the TK04 Thermal Conductivity meter can be equipped with this option). An advantage of the full-space line-source probe is the ability to measure weak or weakly consolidated material with relative ease. All that is required is the application of the probe onto the sample insuring good thermal contact between the probe and the material under study. The needle probe can be either pushed gently into a sample if sufficiently soft or inserted into a small pre-drilled hole if the rock sample is indurated. This process does not require the adjunction of contact paste as in this case the needle probe inserted into the sample ensures necessary thermal contact between the probe and the weak or weakly consolidated material under study. The half-space probe can also be used for measuring the thermal conductivity of drill cuttings. In this instance a geometric mean model of thermal conductivity can be used for calculating the thermal conductivity of the drill cuttings from the measured effective thermal conductivity, C for the saturated mixture of cuttings and saturating fluid, the fluid thermal conductivity and the volume fraction of the fluid in the mixture (Pribnow and Sass 1995). Drill cuttings or fragments of recommended size between 0.05 and 1 mm should be mixed with a fluid such as water (TeKa 2014; Pribnow and Sass 1995). For thermal conductivity measurements, the mixture of drill cuttings and fluid is subjected to a pressure of 0.5–2.5 MPa (5–25 bar). The geometric mean model may be applied if the thermal conductivity of the fluid is lower than the thermal conductivity of the cuttings (TeKa 2014). If water is used the thermal conductivity of the cuttings should be less than 7.5 W/(m K) (TeKa 2014).

The line-source instrument also allows measurements on frozen rock samples at temperatures as low as −25 °C. The recommendations on measurement procedures are available from the manufacturer if required.

6.7 Limitations and Common Sources of Error

A common source of error stems from the level of pressure applied to the sample and the line-source probe. Insufficient pressure promotes poor thermal transfer from the line-source probe to the rock sample and reduces accuracy of thermal conductivity measurement. Conversely excessive pressure can cause partial or full disintegration of porous or fractured rock samples, such as, and especially, fluid-saturated sedimentary rock samples.

If the rock sample surface is not treated and prepared adequately significant thermal resistance may occur between the probe and the sample surface. This results in a systematic error increase in the thermal conductivity measurement. The requirement of a good thermal contact between a rock sample surface and line-source probe is particularly critical for highly porous and/or fractured sedimentary rock samples, whether saturated or not.

Minimal rock sample thickness, length and width should be chosen according to the recommendations of the manufacturer's manual. If the rock sample thickness, length and width deviate from these recommendations, thermal conductivity measurements arguably cannot be meaningful.

Although the rock sample is heated with a distributed line source, the temperature recording is performed with a small temperature sensor located in the line source center. For the thermal conductivity measurements on heterogeneous rock samples, this leads to uncertainties in the measurement results as readings substantially depend on the thermal conductivity of a small local area of the rock sample surrounding the temperature sensor. For example, if the temperature sensor is located above a grain with thermal conductivity value that exceeds the mean thermal conductivity value of the sample, the line-source instrument reading will exceed the average thermal conductivity value of the sample. Conversely, when a zone with reduced thermal conductivity (for example, a crack) is located under the temperature sensor, the reading gives an underestimated thermal conductivity value in comparison with the rock sample true thermal conductivity.

6.8 Metrological Considerations

Two reference standards both with a thermal conductivity of 1.6 W/(m K) are supplied with the TK04 Thermal Conductivity Meter to test the instrument calibration. Nevertheless, practice recommends the use of additional reference samples with thermal conductivity values other than 1.6 W/(m K). Additional reference samples within thermal conductivity of 0.7–1.3 and 2–10 W/(m K) for the standard half-space probe will help to determine the accuracy and precision of the instrument over the whole measuring range.

More detailed recommendations for the metrological testing and control of the line-source instruments are given in Sect. 7.

7 Metrological Testing and Control of Measuring Techniques

Absolute or relative precision (repeatability of results) can be determined by repeat measurements on the same specimens under the same conditions. It should be done on several and different standard specimens or different homogeneous rock samples from 4 to 6 distinct intervals of the thermal property range covered by the technique tested. In effect the precision of the instrument may vary and depends on the thermal property value. Every time a specimen is tested, it should be taken out from the instrument after the measurement, cleaned, prepared again and placed into the measuring device again in the same position to make the next independent measurement for a correct determination of the instrument precision. All measurement results should be processed statistically when (1) an average result is estimated, (2) a standard deviation of the results is estimated, (3) a Student Test coefficient is determined accounting for a total number of independent measurements, (4) absolute and relative precision values are calculated from the given test data with a 0.95 confidence level.

Absolute or relative accuracy can be determined in two ways.

First, thermal properties measurements are undertaken for 4 to 6 different samples of industrial or natural homogeneous materials representative of the whole measurement range of the instrument tested. Thermal properties measurements of the same samples can then be performed using another instrument provided the other instrument has reliably tested metrological parameters. The comparison results should be processed statistically. Absolute and relative accuracy for a 0.95 confidence level can be determined from the test data acquired.

Second, thermal conductivity reference standards are used, as long as the reference standards are either certified by a National Standard Bureau or alternatively are standards of well-known thermal properties such as those listed in Table 6. No less than 4 or 5 reference standards should be used to cover the whole range of thermal properties values measured with the instrument tested. 25–30 independent measurements should be performed with the instrument for each reference standard. Average values of measurement results should be calculated and compared to published data. The comparison results should be processed statistically. Absolute and relative accuracy for a 0.95 confidence level can be determined from the collected test data.

Inter-laboratory testing (most often on core collections) is applied in thermal petrophysics with the participation of two or more petrophysical laboratories. Often the instruments tested have not been metrologically studied previously. In this case a difference in measurement results can only be estimated. If measurements are performed on rock or core samples, 3D heterogeneity may influence the results and hinder a valid comparison of results. This is mostly due to heat sources and local temperature sensors being located in different areas of the same heterogeneous rock sample. Furthermore, when results from different laboratories and/or instruments are internally consistent for identical homogeneous industrial material samples, it only implies that the accuracy of the instruments tested is about the same; it does not provide an absolute value of accuracy which in this case remains unknown.

For the optical scanning instruments, the accuracy of the volumetric heat capacity (via thermal diffusivity) measurement can also be tested with dedicated measurements of specific heat, *c*, using a high-precision standard calorimeter (e.g. a Setaram BT2.15 calorimeter is used to this effect at the Schlumberger Moscow Research Center) and density measurements via well-known techniques. Then volumetric heat capacity values are calculated (1) from thermal conductivity and thermal diffusivity measured on the same sample with the optical scanning technique, and (2) from the specific heat determined with the calorimeter, and (3) the density. Results obtained from the two techniques can be compared. Usually, the quality of measurement and accuracy of volumetric heat capacity obtained with the calorimeter technique is superior to that of the volumetric heat capacity determined by the optical scanning instrument.

8 General Features of Measuring Techniques

Evolution in thermal petrophysics and its active implementation since the 1990s have essentially improved the possibilities for studying rock thermal properties accounting for better measurement quality, rock anisotropy estimation and increase in amount of rock samples to be studied. Long-term metrological comparison of different measuring methods and instruments has demonstrated that there are serious limitations of traditional methods for numerous high-precision simultaneous measurements of thermal conductivity and volumetric heat capacity accounting for rock heterogeneity and anisotropy. Further limitations exist for rocks with high porosities.

The optical scanning, divided-bar and line-source instruments provide different possibilities for thermal properties measurements. The up-to-date techniques provide determination of rock thermal conductivity, thermal diffusivity and volumetric heat capacity separately or simultaneously on the same rock sample. The existing equipment described here allows thermal properties measurements on full size core, split core, core plugs, broken core samples and core cuttings. Continuous profiling of thermal properties on the whole core along a well has now become possible. Rock heterogeneity and anisotropy are essential compositional properties that presently can be estimated with relative ease.

The principal features of traditional and advanced measuring methods and equipment are summarized in Table 7. The table helps in choosing the most appropriate method(s) depending on the application, purpose and outcome of the measurements.

The commercial optical scanning instruments (1) for thermal conductivity measurements, and (2) for thermal conductivity and thermal diffusivity (and volumetric heat capacity) measurements are being manufactured by Lippmann and Rauen GbR (www.tcscan.de).

The commercial divided-bar instrument for thermal conductivity measurements is manufactured by TA Instruments (www.tainstruments.com) and Hot Dry Rocks (www.hotdryrocks.com).

The commercial line-source instrument, TK04 Thermal Conductivity Meter for thermal conductivity measurements, is manufactured by TeKa (http://www.te-ka.de).

9 Specific Heat Measurements

Measurements of specific heat can be performed with commercially available differential scanning calorimeters such as those produced by Setaram (Calvet-C80, BT 2.15, and other models), Netzsch (DSC 204 F1 Phoenix, DSC 214 Polyma, and other models), TA Instruments (Q20, TA-DSC 2920, and other models). In differential scanning calorimetry, the difference in the amount of heat required to increase the temperature of a sample and reference standard is determined as a function of temperature. Both the sample and reference standard are maintained at nearly the same temperature throughout the experiment. The temperature program of differential scanning calorimeters provides a linear temperature increase of the sample holder as a function of time. The reference standard should have a well-known heat capacity over the range of temperatures to be scanned. The measurements can be performed over a wide temperature range with good results and an uncertainty of less than 3 %. Unfortunately, most of the instruments provide specific heat measurements only on small rock samples, typically less than 1 cm^3; this small volume does not permit rock heterogeneity characterization. General recommendations for these measurements can be found in ASTM Standard Test Method for Specific Heat of Rock and Soil (2008).

For most rock thermal properties applications, specific heat values measured with these instruments and procedures would have to be combined with rock density values to calculate the volumetric heat capacity required for heat transfer process modeling. Peculiarities and difficulties of specific heat measurements do not allow to obtain representative data to characterize specific heat variations within rock formations accounting for multiscale formation heterogeneity. Alternatively, the volumetric heat capacity of rock samples measured directly or calculated from experimental results of thermal

Table 6 Thermal conductivity and thermal diffusivity of reference standards

Material	Thermal conductivity [W/(m K)]	Thermal diffusivity (10^{-6} m^2/s)
Plexiglass Sergeev and Shashkov (1983)	0.194 (±0.5 %)	–
Optical glass ‘Heavy Flint TF-1’ Sergeev and Shashkov (1983)	0.701 (±0.3 %)	0.556 (±0.5 %)
Optical glass SF-2 (http://www.newport.com/Optical-Materials)	0.735*	0.383*
Optical glass K-8 Sergeev and Shashkov (1983)	1.094 (±0.3 %)	0.789 (±0.7 %)
Pyrex (http://www.newport.com/Optical-Materials)	1.13*	0.676*
Optical glass ‘Light Crone LK-5′ Sergeev and Shashkov (1983)	1.185 (±0.3 %)	0.779 (±0.7 %)
Optical glass ‘Fused Silica KV’ Sergeev and Shashkov (1983)	1.35 (±1 %)	0.827 (±1 %)
Pyroceram	3.75–4.10*	1.80–1.95*
Titanium alloy VT-6	6.40–6.90*	2.70–2.95*
Quartz single crystal	6.05 (±0.8 %) along axis *C*	3.06 (±1 %) along axis *C*
	10.7 (±1 %) along axes A and B Beck (1987), Popov et al. (1987, 1990)	5.42 (±1.5 %) along axes *A* and *B*
Stainless steel	13.6–14.8*	3.40–3.80*

* Certification from National Standard Bureau is required for more accurate data

Table 7 General features of different techniques for the rock thermal properties measurements at atmospheric conditions

Measuring technique	Optical scanning	Divided-bar	Line-source
Direct measurements on cylindrical surface of full size core samples	Yes	No	No
Direct measurements on split core samples	Yes	No	Yes
Determination of thermal conductivity/thermal diffusivity tensor components on full size and split core samples	Yes	No	Yes
Rock heterogeneity characterization from thermal property profiling	Yes	No	No
Measurement of bulk sample properties	Yes	Yes (with several measurements)	Yes (with several measurements)
Numerous fast measurements	Yes	No	No
Necessity in mechanical treatment of rock samples	No	Yes	Yes
Necessity in special geometry of rock samples	No	Yes	No
Thermal properties measured	Thermal conductivity, thermal diffusivity (hence volumetric heat capacity)	Thermal conductivity	Thermal conductivity
Measurements on standard core plugs (1″ × 1″)	Yes	Yes	No
Measurements on core cuttings	Yes	Yes	Yes
Measurements on weakly consolidated rock samples	Yes	Yes	Yes
Continuous thermal logging on core samples	Yes	No	No
Measurements at elevated temperature and pressure	No	Yes	Yes
Thermal property imaging	Yes	No	No

Table 8 Comparison of isobaric specific heat c_P and latent heat of melting L of granite, basalt, sea and fresh water and dry air (Clauser 2011)

Physical value	Granite	Basalt	Sea water	Fresh water	Dry air (15 °C, 1 atm.)
c_P (kJ/kg/K)	0.83	0.88	3.99	4.18	1.006
L (kJ/kg)	420	420	335	333.55	196

conductivity and thermal diffusivity measurements can be used for specific heat determination if rock sample densities are known.

10 Latent Heat

Freezing and thawing of water in soils or rocks liberate or consume heat, respectively. Comparison of isobaric specific heat c_P and latent heat of melting L of granite, basalt, sea and fresh water is given in Table 8. Phase changes generally consume or deliver much more latent heat than can be stored or delivered as sensible heat: it requires a temperature increase of more than 80 °C to equal by sensible heat the amount of latent heat required to melt 1 kg of sea ice (Table 8).

The latent heat L which corresponds to these additional heat sources and sinks can be elegantly combined with the specific heat of the liquid and solid rock, c_l and c_s, respectively, into an effective specific heat c_{eff}. This effective specific heat then accounts for the entire change in enthalpy H, including latent heat. In this approach, the latent heat effects are assumed to occur between the solidus and liquidus temperatures T_1 and T_2, respectively. The heat liberated by a solidifying ('freezing') liquid phase is obtained by weighting the corresponding contributions by the mass fractions of liquid and solid phases, ϕ_l and ϕ_s, respectively. The enthalpy change of one unit of rock mass (e.g. 1 kg in SI) then becomes

$$\mathrm{d}H_{\text{freezing}} = (\phi_l c_l + \phi_s c_s)\mathrm{d}T + L\mathrm{d}f_l \tag{24}$$

and the effective specific heat c_{eff} is:

$$c_{\text{eff}}^{\text{freezing}} = \frac{\mathrm{d}H}{\mathrm{d}T} = \phi_l c_l + \phi_s c_s + L\frac{\mathrm{d}\phi_l}{\mathrm{d}T} \tag{25}$$

Conversely, when considering melting the solid phase, the enthalpy change of one unit of rock mass is

$$\mathrm{d}H_{\text{melting}} = (\phi_l c_l + \phi_s c_s)\mathrm{d}T + L\mathrm{d}f_s \tag{26}$$

and the effective specific heat in this case c_{eff} is:

$$c_{\text{eff}}^{\text{melting}} = \frac{\mathrm{d}H}{\mathrm{d}T} = \phi_l c_l + \phi_s c_s + L\frac{\mathrm{d}\phi_s}{\mathrm{d}T} \tag{27}$$

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Appendix (to 4.2)

If a point heat source is located at (x', y', z'), the differential equation of heat conduction,

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{a}\frac{\partial T}{\partial t} \tag{28}$$

is satisfied by (Carslaw and Jaeger 1959, Sect. 10.2, p. 256):

$$T = \frac{Q}{8(\pi a t)^{\frac{3}{2}}}\exp\left[-\frac{(x-x')^2+(y-y')^2+(z-z')^2}{4at}\right] \tag{29}$$

where a is the thermal diffusivity (m^2/s), Q is the heat strength (K m^3), more precisely Q is the temperature by which an amount of heat released would raise a unit volume of the medium. As $t \to 0$ the expression (29) tends to zero at all points except (x', y', z'), where it becomes infinite. It is easy to check that the total quantity of heat in the infinite region is equal to QC where C is the volumetric heat capacity.

Consider heat emitted at the origin for times $t > 0$ at the rate q in heat units per unit time (i.e. q in J/s hence W) and an infinite medium moving uniformly past the origin with velocity v parallel to the axis of x. The temperature T can be calculated at a fixed point (x, y, z) at time t. In the infinitesimal time interval $\mathrm{d}t'$ at time t', $q\mathrm{d}t'$ heat units were emitted at the origin at time t' (i.e. $q\mathrm{d}t' = \mathrm{QC}$); also the point of the infinite medium, which at time t is at (x, y, z), was at time t' at [$x - v(t - t')$, y, z]. Thus the temperature T at time t at point (x, y, z) due to the heat $q\mathrm{d}t'$ emitted at t' is, by (29),

$$T(x,y,z,t) = \frac{q\mathrm{d}t'}{8C[\pi a(t-t')]^{\frac{3}{2}}}\exp\left\{-\frac{[x-v(t-t')]^2+y^2+z^2}{4a(t-t')}\right\} \tag{30}$$

and the temperature T at time t due to heat emitted at the origin is

$$T(x,y,z,t) = \frac{q}{8C(\pi a)^{\frac{3}{2}}} \int\limits_0^t - \frac{\exp\left\{-\frac{[x-v(t-t')]^2+y^2+z^2}{4a(t-t')}\right\}}{(t-t')^{\frac{3}{2}}} \mathrm{d}t'$$
$$= \frac{q}{2R\lambda\pi^{\frac{3}{2}}} \exp\left(\frac{vx}{2a}\right) \int\limits_{\frac{R}{2\sqrt{\mathrm{at}}}}^{\infty} \exp\left(-\xi^2 - \frac{v^2R^2}{16a^2\xi^2}\right) \mathrm{d}\xi \quad (31)$$

where $R = \sqrt{x^2 + y^2 + z^2}$.

This is a solution for the amount of heat for finite time t. If $t \rightarrow \infty$, a steady thermal regime is established, and the temperature T at (x, y, z) is given by (Carslaw and Jaeger 1959, Sect. 10.7, p. 267)

$$T(x,y,z) = \frac{q}{4\pi\lambda R} \exp\left[-\frac{v(R-x)}{2a}\right] \quad (32)$$

If the point heat source is located on a surface of a half-infinite medium, the temperature at (x, y, z) is given by:

$$T(x,y,z) = \frac{q}{2\pi\lambda R} \exp\left[-\frac{v(R-x)}{2a}\right]. \quad (33)$$

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