European Geothermal Congress 2013
Pisa, Italy, 3-7 June 2013

Laboratory measurements of rock thermal properties by needle probe and transient divided bar

Thue S. Bording[1], Niels Balling[1], Søren B. Nielsen[1].

[1] Department of Geoscience, Aarhus University, Høegh-Guldbergs Gade 2, 8000 Aarhus C, Denmark

Thue.bording@geo.au.dk

Keywords: Thermal conductivity, thermal diffusivity, transient, divided bar, needle probe.

ABSTRACT

In this study we present first results of improvements to the classical divided bar and needle probe methods for measuring rock thermal properties. Both methods are fairly accurate in determining thermal conductivity using approximate analytical expressions, whereas thermal diffusivity and heat capacity are generally not measured. The improvements we implement in order to measure these properties as well, include, for both methods, a combination of fast numerical finite element forward modelling and a Markov Chain Monte Carlo inversion scheme for estimating parameters.

In order to extend the classical divided bar method to measure thermal diffusivity in addition to conductivity, the apparatus is run in a transient mode. Temperatures are measured as a function of time across the stack of rock sample and standards. At the upper surface of the stack, a time varying temperature is imposed. By Monte Carlo inversion of the associated transient data set, thermal conductivity as well as thermal diffusivity and heat capacity may be measured with high accuracy.

The needle probe, consisting of a thin cylinder containing a heating wire and a thermistor, is inserted into the rock sample to be measured. The probe and the surrounding sample are heated, and the thermistor measures the temperature increase at the probe centre. We apply a numerical forward model and use the entire temperature response to measure thermal conductivity, with the potential of estimating thermal diffusivity as well.

1. INTRODUCTION

In geothermal exploration, some of the key elements in understanding and predicting the subsurface thermal regime are the rock thermal properties. These properties include thermal conductivity, thermal diffusivity and heat capacity. Thermal conductivity governs the steady-state undisturbed thermal regime, whereas thermal diffusivity is important for the transient behaviour of the thermal regime, e.g. in relation to production-injection schemes and for disturbances in relation to drilling boreholes. Reliable determination of these parameters is therefore of crucial importance.

Thermal diffusivity, □ is defined by the following relation:

$$\square = k/(\rho c_{p}) \qquad [1]$$

where k is thermal conductivity, ρ is density and c_p is specific heat capacity. Since density is fairly precisely measured by independent methods, we concentrate on the parameters: conductivity, specific heat capacity and diffusivity.

The classical needle probe and divided bar methods give reliable estimates of the thermal conductivity, but thermal diffusivity and specific heat capacity are generally not measured. We present methodological improvements to both methods which allow for measuring these additional parameters with little or no modification of traditional equipment. Our procedure for parameter estimation is based on a combination of fast numerical finite element forward modelling of total temperature time series and Markov Chain Monte Carlo inversion schemes.

2. TRANSIENT DIVIDED BAR METHOD

The main principles of our divided bar apparatus (Fig. 1) are similar to those used by Beck (1957) and Jessop (1970). It consists of cylindrical discs of diameter 5 cm. The setup employs a double standard of ceramic material with known thermal properties. Two copper discs (thickness 6 mm) are placed between the ceramic standards and the sample. Four thermistors in the copper discs measure the temperatures in the radial centre of the stack at positions above and below both ceramic standards (Fig. 1). At the upper limit of the stack, a time varying temperature is imposed by circulating water of variable temperature. In order to minimize non-axial heat flow, the maximum and minimum temperatures are chosen to be symmetrical around the ambient temperature.

Uniaxial pressure of about 1 MPa is applied to the stack to reduce surface resistance between discs. A silicone based heating compound may be applied to the surfaces of the discs to limit the influence of any surface irregularities. The stack is encased and insulated by Styrofoam to limit convection and non-axial heat flow.

The temperatures at the four thermistor points are measured every 0.2 seconds. In the forward modelling, the temperatures of top and bottom thermistors are used as boundary conditions for the numerical simulation. The data fitted in the inversion are the temperatures of the middle thermistors.

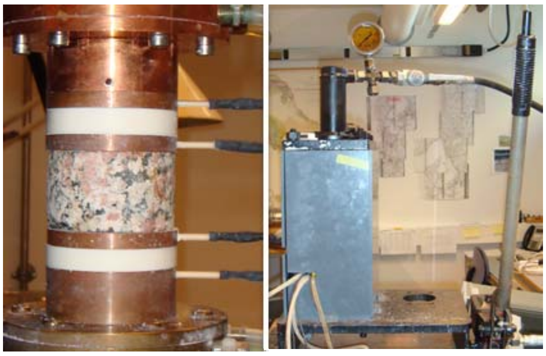

Figure 1: (Left) The divided bar setup with two ceramic standards and a granite sample. The four thermistor sensors are seen to the right. (Right) The encased stack and piston for pressure.

2.1 Forward modelling

The forward modelling of the full time series temperature distribution is carried out using the finite element method. Although the heat equation is solved only for one-dimensional axial flow, the possibility of radial heat flow is accommodated by applying a radiation boundary condition that allows the stack to exchange heat with the surroundings. This is governed by a surface conductance (constant along the stack, but variable) and a driving temperature given by the difference between the stack temperature and the ambient temperature. The sample, the copper discs and the ceramic standards are all assigned values of thermal conductivity, specific heat capacity, and density. The thermal resistance at the six internal surfaces of contact is also treated using a radiation boundary condition, resulting, in principle, in six unknown surface conductances. The temperatures measured in the top and bottom thermistors are used as Dirichlet boundary conditions for each time step (Fig. 2).

For each time step, the temperatures in the positions of the two middle thermistors are stored and used in the inversion algorithm.

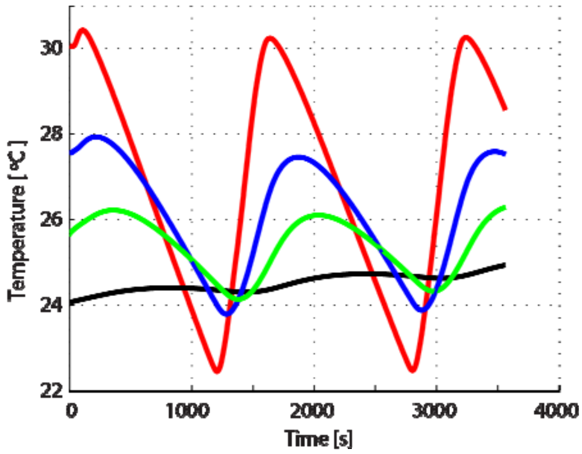

Figure 2: Example of measured temperatures in the divided bar stack. Red, blue, green and black are thermistor temperatures from top to bottom.

2.2 Inversion modelling

A Markov chain Monte Carlo Metropolis-Hastings (MCMCMH) inversion algorithm (Hastings 1970) is applied. The MCMCMH algorithm performs a statistical sampling of the model parameter space and estimation of statistical properties of the model parameter values. The forward modelling is fast enough that sufficiently long Markov chains (e.g. 150.000) can be generated to produce representative posterior probability density functions for the variable parameters.

In the inversion procedure we keep several parameters as unknown; however most are bound by a priori knowledge. The parameters included in the inversion scheme are the thermal conductivity, specific heat capacity and density of the sample, copper and ceramic standard discs, the surface conductances between the discs and the radial surface conductance. All parameters, except the main unknowns which are the thermal conductivity and specific heat capacity of the sample, have a priori values with uncertainties. The a priori values for the standard material and the copper discs and the density of the sample are measured by independent methods and have very low uncertainties. The surface conductances and radial surface conductance are estimated by calibration and have larger uncertainties.

An example of measurements, with parameters of the accepted models presented in histograms, is shown in Fig. 3.

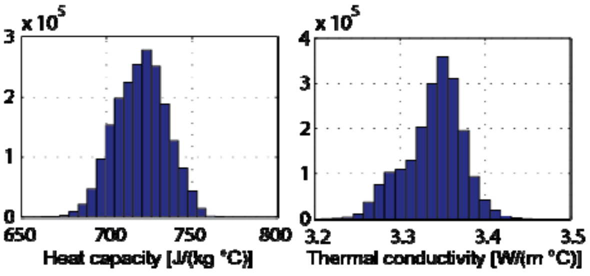

Figure 3: Example of measuring result from the transient divided bar.

3. NEEDLE PROBE METHOD

Our needle probes are of own construction with main principles as shown in Fig. 4. The needle contains a heating wire and a thermistor placed in its radial and longitudinal centre, encased in an insulated tube. The heating wire is placed outside the insulated tube and extends along the active part of the needle. The insulated tube and the heating wire are encased in an outer brass tube. The applied probes have lengths of c. 50 and c. 80 mm and an outer diameter of 1.5 mm.

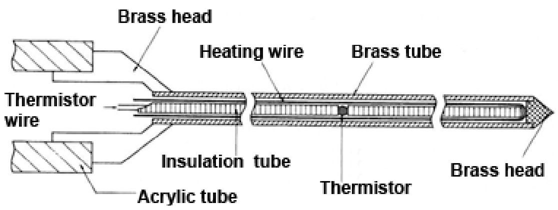

Figure 4: Main construction principles of the needle probe.

Measurements are carried out by inserting the needle probe into the sample to be measured. It is well suited for unconsolidated sediments, but may equally well be applied to any type of rock when accurately fitting holes can be made for the probe. It is important to ensure a good contact between needle probe and sample. If necessary, a silicone based heating compound can be applied. The dimension and geometry of the sample must comply with some minimum requirements. The model used for the forward solution applies cylindrical geometry.

Most measurements are carried out on water saturated samples. Before measurements, the sample is typically submerged in water or water saturated sand. This ensures a stable ambient temperature and reduces the risk of edge effects on small samples. When thermal equilibrium in the sample is established, a constant current is passed through the heating wire. The thermistor measures the temperature before heating commences and the temperature increases during heating. Sampling rate is typically 0.2 s. To avoid edge effects, the applied total sampling length depends on the length of the applied probe and the size of the sample.

3.1 Forward modelling

Traditionally, analytical solutions of varying complexity have been used in calculating the forward response (Von Herzen and Maxwell 1959, Kristiansen 1982). We apply a numerical finite element procedure which enables accurate modelling of the entire temperature response. The forward model assumes radial symmetry, and the radial heat flow is integrated over the surface area. The longitudinal length of the system is considered infinite. These simplifications allow us to reduce the three-dimensional problem into a single-dimensional problem, thereby greatly increasing computation speed. By this model, however, effects of a finite probe length are not estimated.

The model probe is considered homogenous with a source term equal to the heat produced by the heating wire. The contact between the needle probe and sample is treated as a radiation boundary condition, resulting in an unknown surface conductance. The parameters of the needle probe and the sample are density, specific heat capacity and thermal conductivity. The needle probe parameters are determined by calibration. At the outer surface of the sample, the temperature is fixed at ambient temperature. At the centre of the probe a no-flow boundary condition is applied.

3.2 Inversion modelling

The inversion method used for the needle probe data is the MCMCMH algorithm. The density, specific heat capacity and thermal conductivity of the needle probe are fixed in the inversion and found by calibration in standards of known thermal properties. The density of the sample is found by independent methods. The thermal conductivity and specific heat capacity of the sample are kept unknown, while the surface conductance has a priori value with uncertainty.

Fig. 5 shows an example of a needle probe temperature response. Thermal conductivity and thermal diffusivity of the samples are 2.0 W/(m °C) and 1.2 mm^2/s, respectively.

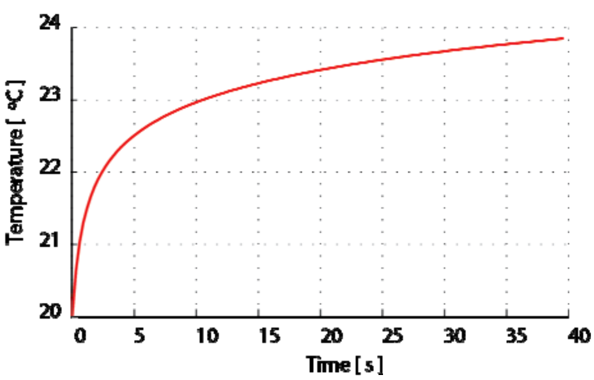

Figure 5: Example of temperature response in a needle probe measurement.

Preliminary experimental results indicate that thermal diffusivity may be accurately measured only if the thermal parameters of the needle have been determined by careful calibration. This is because the diffusivities of both the needle and the sample are involved in the first rapid rise of temperature. At later times, the diffusivities are not involved as the temperature rise is governed by the long-time solution, which depends only on the rate of heat supply and the thermal conductivity of the sample (e.g. Kristiansen, 1982).

4. CONCLUSIONS

With the suggested transient procedure, the divided bar, in addition to thermal conductivity, measures also specific heat capacity and thermal diffusivity. All properties may be measured with a high degree of accuracy. To measure specific heat capacity and thermal diffusivity by the needle probe, the probe parameters need to be determined by careful calibration.

For the transient divided bar, the improvements only require little or no modifications to existing setups. The system must be able to measure in a continuous mode and with a varying temperature boundary. The finite element method is easily applied to different configurations of standards and samples. The MCMCMH algorithm can be applied to any problem with a forward solution, but high computation speed is essential to produce long Markov chains.

REFERENCES

Beck, A.: A steady state method for the rapid measurement of the thermal conductivity of rocks, *Journal of Scienctific Instruments,* **34**, (1957), 186-189.

Hastings, W.K.: Monte Carlo sampling methods using Markov chains and their applications, *Biometrika* **57**, (1970), 97-109.

Jessop, A.M.: The effect of environment on divided bar measurements, *Tectonophysics,* **10**, Issues 1-3, (1970), 39-49

Kristiansen, J.: The transient cylindrical probe method for determination of thermal parameters of earth materials, *Geoskrifter*, **18**, Department of Geology, Aarhus University, Denmark, (1982)

Von Herzen, R. and Maxwell, A.E.: The measurement of thermal conductivity of deep-sea sediments by a needle-probe method, *Journal of Geophysical Research*, **64**, (1959), 1557-1563

Acknowledgements

This study is supported by the Danish Council for Strategic Research.