The Portable Electronic Divided Bar (PEDB): a Tool for Measuring Thermal Conductivity of Rock Samples

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The thermal conductivity of a geological formation is an essential physical property to be determined when attempting to understand and model heat flow. The Portable Electronic Divided Bar (PEDB) is an effective tool in measuring thermal conductivity, and is currently playing an important role in the development of heat flow modelling of Australian geothermal resources.

The PEDB is an electronic apparatus that produces a temperature gradient across a specially prepared rock sample; and with its precision heat flow monitoring system, it allows thermal conductivity of a rock sample to be determined via the application of Fourier's Law. A simple spreadsheet allows direct temperature measurements—utilizing thermocouples—to be recorded and interpreted to provide an absolute thermal conductivity value within ±3.5%. Measurements are rapid, taking from 5 to 15 minutes per sample.

In addition to uniaxial thermal conductivity measurements, biaxial and triaxial measurements can be made with the PEDB, allowing for studies of thermal conductivity anisotropy. Cylindrical core as well as irregularly shaped rock samples can be measured.

The Divided Bar was first described as a steady-state tool used to measure the thermal conductivity of materials by Benfield in 1939 (Beardsmore and Cull, 2001). The Portable Electronic Divided Bar (PEDB) is a development of Benfield's divided bar operating principal, utilizing advancements in technology to create a high accuracy (±3.5%), light-weight (less than 5 kg), small size (260 mm x 310 mm x 450 mm) and low power consumption (less than 200W), low noise production device.

In the field it is valuable for measuring the thermal conductivity of rock samples immediately after recovery from drilling, maintaining as closely as possible the rock's in-situ porosity and moisture content.

For use in laboratory settings, the space that is required is the corner of an office desk, a single AC power outlet, and a PC and logging device.

Keywords: PEDB, portable electronic divided bar, thermal conductivity, heat flow, anisotropy

Thermal Conductivity and Heat Flow

Observing Fourier's Law:

$$Q = \lambda \times \beta \quad (1)$$

Q, λ, and β are heat flow (W/m^2), thermal conductivity (W/mK), and thermal gradient (K/m), respectively.

The heat flow of a site can be derived by utilising a combination of: 1) thermal conductivity measurements to define λ; and 2) down-hole temperature logging to define β. Determining heat flow requires consideration of the geologic formations from which the thermal conductivity samples came, and so rock samples that are to be tested for thermal conductivity must be carefully chosen to ensure they are appropriately representative of those geologic formations, with attention paid to characteristics such as lithology and porosity.

If thermal conductivity measurements from several geological formations are taken, it is possible to develop a down-hole profile of thermal conductivity.

Calculation of Thermal Conductivity

Thermal conductivity of a rock sample, as measured by a PEDB, is determined by:

$$\lambda = \frac{d}{R} \quad (2)$$

λ = thermal conductivity

d = thickness of the sample in mm

R = (A (ΔT- c))/(a (diameter + b))

A = surface area of sample in mm^2

a, b, c, are calibration constants determined during the calibration process.

ΔT is defined by:

$$\Delta T = \frac{T_2 - T_3}{(T_1 - T_2) + (T_3 - T_4)} \quad (3)$$

T_1, T_2, T_3, T_4 = temperatures of PEDB plates as shown on Figure 1.

The thermal conductivity of each rock sample is calculated using the measurements of the three values d, A, and ΔT, where ΔT is the ratio of the temperature drop across the sample relative to the sum of temperature drops across the polycarbonate layers within each plate-pair—a unit-less quantity.

The measurements of *d* and A are made utilising precision callipers; the measurement of ΔT is made utilising the PEDB, a PC, and a digital logging device.

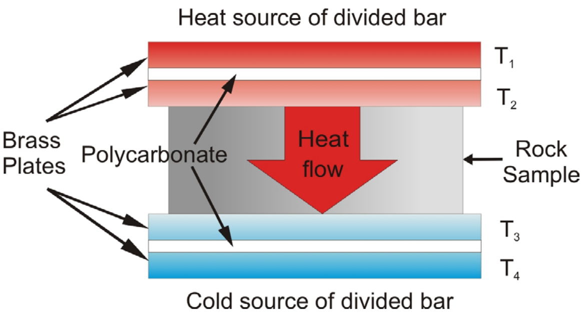

Figure 1: Diagram showing principal components of the plates of the PEDB. Each brass plate is fitted with a separate thermocouple; ΔT is the ratio of the temperature of the plates of the PEDB: $\Delta T = (T_2 - T_3)/((T_1 - T_2)+(T_3 - T_4))$. The heat source is above the top pair of brass plates, and the cold source is below the bottom pair; the consequence is that heat flows across the rock sample.

The PEDB

Power supply

The PEDB has a 'universal' power supply, capable of being powered by mains sources that are within 100-250 VAC, 45-70 Hz. Portability of the PEDB can be achieved by using a sine-wave generator, a sine-wave inverter rated for 200 W from a power source such as an automobile, or from a DC source.

Plates of the PEDB

Two pairs of highly thermally conductive plates—brass in the case of the PEDB—are used, each with a layer of polycarbonate in between, comprising a brass-polycarbonate-brass assembly that resembles a sandwich, as shown in Figure 2. Each of these assemblies has a thickness of approximately 7mm and a diameter of 65 mm. One of the assemblies is situated on top of the rock sample—thermally connected to a heat source—and the other assembly is below the sample—thermally connected to a cold source. Such an orientation prevents: 1) convection from occurring between the plates and; 2) resultant introduced uncertainties.

Within each of the four brass plates is embedded a thermocouple with its welded joint located in the centre of the brass plate. Thus the temperatures of each brass plate can independently be measured and used to determine λ.

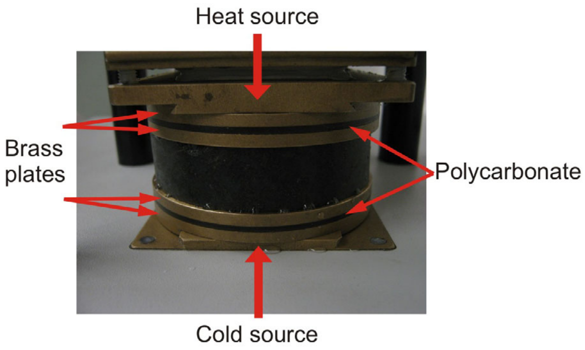

Figure 2: The plates of the PEDB. An HQ sized rock sample is in place and ready for thermal conductivity measurement. Each pair of plates is brass, with a polycarbonate layer in between. Above the upper plate is a heat source, and below the lower plate is the cold source--a thermal gradient across the sample is created; the ratio of the temperature drops across each of the polycarbonate layers and the sample is

Sample preparation

The PEDB measures the thermal conductivity of consolidated drill core. Samples measured for thermal conductivity can be any size up to a diameter of to 65 mm (approximate size of HQ core is 60mm). The samples should be cut so that the two faces of the sample produced are approximately parallel, although precise parallelism is not essential, owing to a swivel-head which allows for measurement of samples that are not perfectly parallel (Figure 3); sample preparation is consequently easier than with systems that do not allow for sub-parallel sample faces.

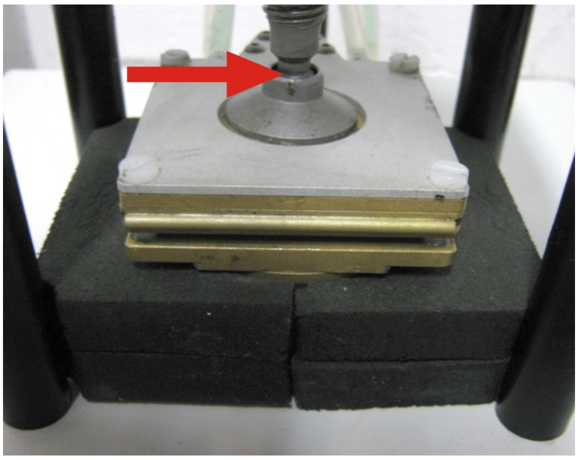

Figure 3: The swivel head (indicated by arrow) of the PEDB allows for thermal conductivity measurements of samples to be made without necessitating perfect parallelism between sample faces. Additionally, the black insulation shown is effective in minimizing thermal loss from the sample.

It is however essential that the faces of the rock sample are flat. This can be accomplished by using a flat grinding wheel and lap-wheel combination, which has been HDRPL's preferred method for processing thermal conductivity samples thus far. The system of sample preparation should be standardized. Generally, polishing to a fine grade up to 600-grit is recommended.

If the samples being measured for thermal conductivity were saturated with water *in situ*, all efforts should be made to preserve the inter-pore water within the core sample. If this is not practicable, then the sample should be re-saturated before measurement via vacuum saturation. In such cases the samples are subjected to a vacuum for a standardized time before being submerged in water and returned to atmospheric pressure for a standardized time, whereafter they can be measured for thermal conductivity.

Importance of sample preparation quality

It has been observed that samples prepared with sub-flat faces or surface irregularities can return significantly lower measured thermal conductivity values. Examples of surface irregularities that have resulted in significant decrease in apparent thermal conductivity are:

- Convex sample faces resulting from worn grinding and polishing wheels.
- Grooved sample faces left over from the rock-sawing process; chips that have fractured from the sample during cutting.
- Pitted surfaces resulting from preparation of weakly consolidated rocks susceptible to “plucking” of grains.
- Sub horizontal fractures and/or joints.

As zones of low thermal conductivity and high water/air content that are created either within the sample itself or along the sample/plate contact, these irregularities effectively impede the heat flow across the sample. Careful efforts—implemented during sample selection, preparation, and measurement—are essential for producing representative thermal conductivity results. The overwhelming majority of core samples that have been encountered by the author during conductivity measurement have provided useful samples for reliable thermal conductivity measurements, when carefully prepared.

Relevance of size and shape of samples tested in the PEDB

Irregularly shaped rock samples can be measured. The accuracy of thermal conductivity measurements is independent of sample shape so long as thermal loss around the perimeter of the sample is minimized. Generally, the thermal loss that may exist for a sample would increase as its surface area increases, but this tendency is effectively controlled with the use of thermal insulation around the PEDB plates and rock sample (Figure) which prevents environmental air circulation from interfering with thermal conductivity measurements.

Figure and Figure 5 show examples of measurements that were made on differently shaped rock samples. In both cases, samples were ground flat, polished, and were of a variable siltstone lithology. Variation in thermal conductivity was 5% or less from the mean in both cases, consistent with normal inter-sample variation.

The dimensions of a rock sample that must be measured when calculating thermal conductivity are thickness and heat flux cross-section. Thickness is measured with precision calipers. Heat flux cross-section can found by measuring the surface area of the rock sample’s face, either by calculating from core diameter, or by tracing the sample and measuring the surface area of the tracing digitally (via scanner and digital graphics software) or on to graph paper. Experiments have shown that variations in results of measurements made via the tracing method and via the calculation from diameter method are within 0.7% variation from the mean.

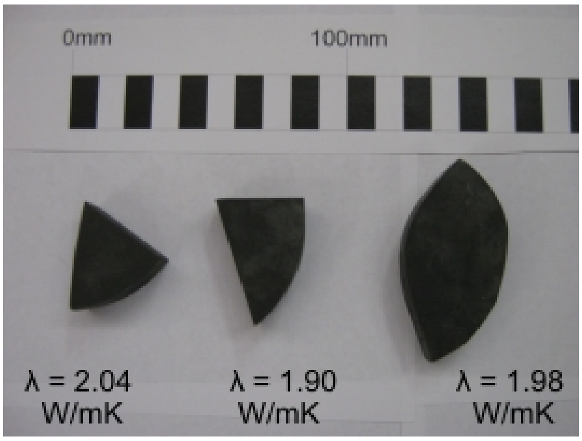

Figure 4: Although varying significantly in size and shape, these samples—which were taken from the same rock specimen—provide consistent results. Their conductivities are 2.04, 1.90, and 1.98 W/mK respectively, representing a range of 3.5% from the mean conductivity of 1.97 W/mK.

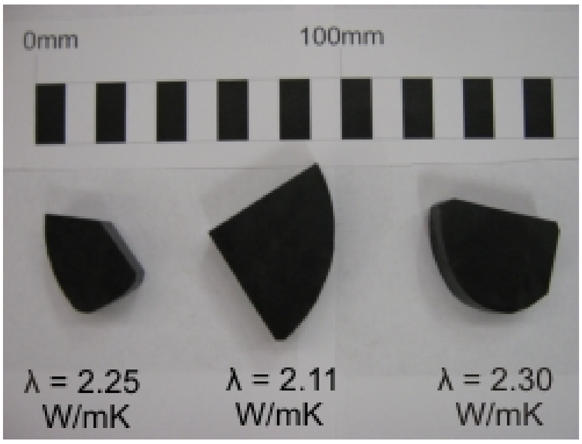

Figure 5: Although varying significantly in size and shape, these samples—taken from the same specimen—provide consistent results. Their conductivities are 2.25, 2.11, and 2.30 W/mK respectively, representing a range of 5% from the mean conductivity of 2.22 W/mK.

Mean Sample Temperature of the PEDB

The PEDB operates best when the mean sample temperature is near the environmental air temperature. To facilitate field operations, the PEDB is capable of operating at a range of mean temperatures, from approximately 10–35°C, and has an indication system showing when the mean temperature approximates the environmental temperature.

Thermal conductivity for rocks is dependent upon temperature, generally becoming less conductive with increasing temperature, at a rate of approximately 0.16% per degree Celcius (Vosteen and Schellschmidt, 2003). This must be kept in mind when determining the thermal conductivity of geological formations, where the *in-situ* temperature is greater than that at which the laboratory tests were made.

Equilibration Process

Once the sample is placed between the plates of the PEDB and slight pressure is applied to the sample via the hand-operated clamp, a temperature gradient is imposed across the sample and thermal equilibrium typically occurs within 5–15 minutes. The time required is dependent upon sample thickness and surface area, and upon the thermal characteristics of the rock sample—most importantly, thermal diffusivity. A sample will equilibrate relatively quickly if it is thin, and has a high surface area and thermal diffusivity. Alternatively, a sample will take longer to equilibrate if it is very thick, and has a low surface area and thermal diffusivity. Figure 6 and Figure 7 represent 1000 seconds of recorded data from the same thermal conductivity measurement.

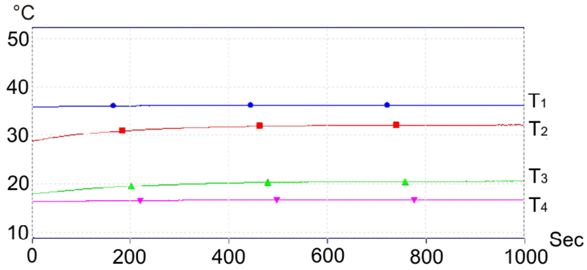

Figure 6: Example of data collected during thermal conductivity measurement; the horizontal axis is time, measured in seconds, and the vertical axis is temperature measured in °C. Each plot represents the temperature of a plate of the PEDB, T_1–T_4, where the hot plate (T_1) in this case is approximately 35°C, the cold plate (T_4) is approximately 17°C, and the intermediate plates (T_2 and T_3), after having a rock sample placed in between them, gradually increase in temperature until thermal equilibrium is reached.

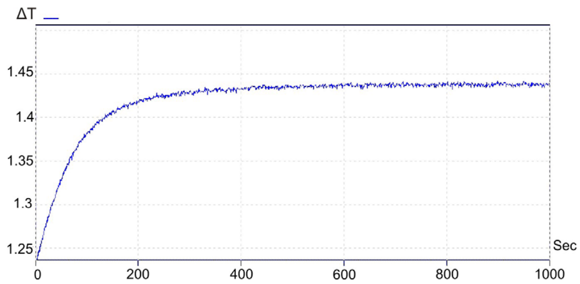

Figure 7: Example of data collected during thermal conductivity measurement; the horizontal axis is time, measured in seconds, and the vertical axis is ΔT. In this example, the sample measured for thermal conductivity is fully equilibrated after approximately 600s, to a ΔT value of 1.44.

Calibration of the PEDB

The PEDB is calibrated using a set of standards of known thermal conductivity. These standards are of differing thicknesses and surface areas, enabling the PEDB to be used for measuring diversely shaped samples, and samples with a range of thicknesses and surface areas.

During calibration, standards are placed in the PEDB individually and measurements are made of the four plate temperatures T_1–T_4 and the derived ΔT value once the standard has reached thermal equilibrium.

Measurement of thermal conductivity anisotropy

Anisotropy is the characteristic of a material to behave differently in one direction with respect to another. Rocks can be thermally anisotropic, and in so being can exhibit different thermal conductivity in different directions.

Typically, thermal conductivity measurements are made along the long axis of a core specimen. During such testing, it is the expectation of the heat flow modeller that the core specimen was taken from a bore that was drilled nearly vertically, and therefore was sufficiently parallel to Earth's heat flow that the need for understanding how heat travels laterally across the core specimen is negated.

Testing for thermal conductivity anisotropy of a rock sample involves biaxial or triaxial measurements. The preparation of cube-shaped samples allows thermal conductivity to be measured along each axis of the same sample; thus, one sample can provide the minimum data required for the creation of an ellipsoidal thermal model. Alternatively, three orthogonally oriented samples can be prepared from a common specimen, collectively providing data for the creation of an ellipsoidal thermal model.

For foliated meta-sedimentary specimens, the tendency has been observed (Figure 8) for thermal conductivity to be greater parallel to the foliation, compared to perpendicular to the foliation. In this paper, λ_1 is nominated as the axis of greatest thermal conductivity, while λ_2 is nominated the axis of least thermal conductivity, and it is assumed that there is an elliptical gradation between λ_1 and λ_2.

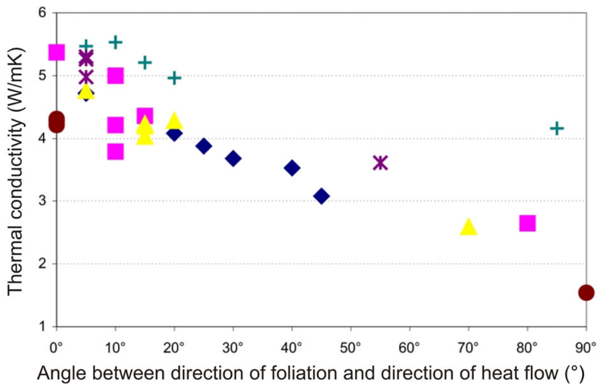

Figure 8: Summary of thermal conductivity data from six meta-sedimentary rock specimens; the six differently shaped symbols indicating the different specimens studied. Each specimen was measured for thermal conductivity at several angles with respect to the specimen's foliation. The vertical axis is thermal conductivity (W/mK); the horizontal axis is the angle between the foliation of the rock sample, and the direction of heat flow across the rock sample while within the PEDB, measured in degrees (°), where 0° indicates heat flow parallel to the planes of foliation, and 90° indicates heat flow perpendicular to the planes of foliation. A relationship is shown to exist between the magnitude of thermal conductivity and the direction of heat flow with respect to the specimen's foliation.

Results of anisotropy testing

The results of two extreme cases of rock thermal conductivity anisotropy are shown in Figure 8 and discussed below.

A foliated meta-sediment, Specimen A had a mean conductivity of 4.26 W/mK parallel to foliation, and a mean conductivity of 1.44 W/mK perpendicular to foliation. That is a variation of 50% from the mean conductivity of 2.85 W/mK. The anisotropy factor for Specimen A expressed as λ_1/λ_2, is 2.96.

Another foliated meta-sediment, Specimen B, had a mean conductivity of 5.37 W/mK parallel to foliation, and a mean conductivity of 2.65 W/mK perpendicular to foliation. That is a variation of 34% from the mean conductivity of 4.01 W/mK. The anisotropy factor for Specimen B expressed as λ_1/λ_2, is 2.03.

In both cases, λ_1 was parallel to the rock specimen's foliation, while λ_2 was perpendicular to the rock specimen's foliation. In addition, λ_1 and the foliation were within 5° of parallel to the bore in both cases. Since the bores that these samples originated from were vertical, the thermal conductivities that would be most relevant to the heat-flow modeller—for the location within the geological formation from which the specimens came—would be those that were parallel to Earth's heat flow, and in these cases parallel to λ_1. The conductivity values most relevant for heat flow modelling of geological formations represented by specimens A and B, would be 4.26 W/mK and 5.37 W/mK respectively.

Calculation of variability in thermal conductivity

But what if the bores, foliation, and the direction of λ_1 discussed immediately above were NOT parallel to Earth's heat flow, and happened to be dipping at 45° instead, as it might in a steeply-dipping mineral exploration bore? In such a case, Earth's heat flow is now no longer parallel with the bore, but is 45° to it; and consequently, the thermal conductivity vector of the rock specimen most relevant to the heat flow modeller is that which is parallel to the direction of Earth's heat flow. Using an elliptical thermal conductivity blending model, where λ_1 and λ_2 are the vectors representing the greatest and lowest thermal conductivities respectively, the resultant thermal conductivity vector for 45° can be determined.

The elliptical model is derived beginning with the equation for an ellipse:

$$1 = \frac{x^2}{a^2} + \frac{y^2}{b^2} \qquad (4)$$

$x = \lambda \cos \theta$

$y = \lambda \sin \theta$

$a = \lambda_1$

$b = \lambda_2$

λ = resultant thermal conductivity when heat flow is at angle θ

λ_1 = vector of greatest thermal conductivity

λ_2 = vector of least thermal conductivity

θ = angle in (°) between the direction of Earth's heat flow and λ_1

Substituting variable into Equation (4) gives:

$$1 = \frac{\lambda^2 \cos^2 \theta}{\lambda_1} + \frac{\lambda^2 \sin^2 \theta}{\lambda_2} \qquad (5)$$

Solving for λ in Equation (5) gives:

$$\lambda = \sqrt{\frac{1}{\frac{\cos^2 \theta}{\lambda_1} + \frac{\sin^2 \theta}{\lambda_2}}} \qquad (6)$$

By applying the λ_1 and λ_2 data from the results of anisotropy testing into Equation (6), the equivalent uniaxial thermal conductivity of the rock samples A and B can be determined:

Sample A:

λ_1 = 4.26 W/mK and λ_2 = 1.44 W/mK

The resultant λ when λ_1 is dipping at 45° is: 1.93 W/mK

Sample B:

λ_1 = 5.37 W/mK and λ_2 = 2.65 W/mK

The resultant λ when λ_1 is dipping at 45° is: 3.36 W/mK

Significance of variability in thermal conductivity

The resultant λ of sample A and B at 45° is 1.93 and 3.36 W/mK respectively. These values are significantly different than either of their respective λ_1 or λ_2 values.

Sample A

55% variation from λ_1 (4.26 W/mK)

34% variation from λ_2 (1.44W/mK)

Sample B

37% variation from λ_1 (5.37 W/mK)

27% variation from λ_2 (2.65 W/mK)

When entered into a heat flow model, this variation in measured thermal conductivity may result in significant variation of calculated heat flow.

While bores drilled purposefully for geothermal energy exploration may as a rule be vertical, bores such as those used for minerals exploration may be significantly non-vertical owing to the efforts of the exploration program to maximize the likelihood of hitting a target lode. Thus, care should be taken when utilizing core from non-vertical bores for geothermal data, ensuring that thermal conductivity anisotropy is accounted for when developing heat flow models.

Limitations of the PEDB

The PEDB is not calibrated for measuring conductivities of samples larger than 65 mm in diameter. Larger core or hand specimens can however be accommodated by cutting them to a suitable size.

The PEDB provides thermal conductivity measurements at mean temperatures from 15–35°C. Considerations of the geological formation's *in-situ* temperature should be made, since thermal conductivity in rocks is a property that generally decreases with increasing temperature.

Conclusions

The PEDB is effective in measuring thermal conductivity of rock specimens:

- Rapidly and on a production scale
- In remote locations and in the laboratory
- Using variable power supplies
- That have a non-standardized size and shape
- Triaxially for thermal conductivity anisotropy studies
- In parallel (two PEDB's can be operated simultaneously)

References

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