ABSTRACT

A laboratory experimental system was designed and validated for measuring thermal properties (heat conductivity and specific heat) on cylindrical rock samples. The experimental setup includes four semi-insulated cells holding cylindrical rock samples; four heaters at the bottom of the samples; and four temperature probe loggers, mounted in holes drilled at the top of the samples. A fused quartz QU1 benchmark sample was used for calibration of the experimental system, i.e. estimation of the heaters’ rates and probe heat capacity. For each of the test runs, four rock samples were used. During the first test run, the heaters were switched on for a specified time and then turned off for temperature recovery. The second, third, and fourth test runs were repeated for all samples, changing their places in four cells correspondingly. Temperature records were obtained over the entire duration of the tests. For each sample, the temperature data were inverted using iTOUGH2-EOS3 to estimate 6 unknown parameters: thermal conductivity, specific heat, and four values of the heat exchange coefficients of the semi-insulated cells. The uncertainties of the estimated parameters were reasonable, i.e., the standard deviations were a few percents of the parameter value. Estimates of the thermal properties of 27 rock samples from different volcanogenic rocks (rhyolite tuffs and lavas Triassic and Quaternary age) were obtained.

INPUT SAMPLES

Core samples for this study were collected during well drilling at the depth interval 2580-2800 m. Geochemical properties of the Rogozhnkovsky volcanogenic rocks were described by Shadrina (2009); the rocks were characterized as rhyolite tuffs, lavas and breccias, composed of the following dominant minerals: quartz (volume fraction 27%), K-feldspar (23%), and albite (28%). Optical petrological studies (M. Puzankov, 2010, pers. com.) confirm significant hydrothermal alteration.

The total number of rock samples used for the thermal properties study is 38 (pore fluids were washed out and the samples dried before the tests). Each sample is a cylinder 50 mm high and 50 mm in diameter. Grain density and porosity were estimated independently from the thermal properties study; the average porosity and permeability are 0.17 and 1.78 mD, respectively (T. Korovina, pers. com. 2009).

LABORATORY EXPERIMENTAL SETUP

The laboratory experimental system includes four heaters (<12 W) and four insulated cylindrical cells, which hold the samples and four temperature probe loggers (Hioki 3447-01, accuracy 0.1°C) (Figs. 1 and 2). At the top of each sample, a small hole (10 mm deep and 2.4 mm diameter) was drilled for temperature probe logger installation (Figs. 2 and 3).

To achieve constant initial temperature conditions the laboratory experimental system was deployed in a special underground room (with maximum daily temperature variations less than 0.5°C), where at least 18 hours between experiments were allowed for equilibration. Temperature records started 5 min before the heaters were switched on (these records yield initial sample temperatures), then the heaters were on for 10 min, and then off for a 3 hour temperature build-up period. Temperature was recorded every 10 s, to be used as observational data for inverse modeling.

NUMERICAL MODEL SETUP

A numerical model using the TOUGH2 code (Pruess et al., 1999) was developed for modeling 3D
multiphase multi-component fluid flow and transport in fractured and porous media.

Since the samples were dried before the experiments, the pore space is assumed to be occupied mostly by air. Hence, the initial gas saturation in the model was set to 0.9999, and the EOS3 equation-of-state module was used. In spite of the thermal insulation, some heat losses occur through the cylinder’s side and top surfaces. These losses are accounted for by specifying Dirichlet boundary conditions, assigned at one external inactive model element (with fixed initial temperature) connected to all the sides and top surface model elements.

A radially symmetric grid was used to represent the cylinder rock sample (Fig. 3). This grid includes 26 layers and 12 radial zones. Each layer thickness is 2 mm, and radial zones were assigned with logarithmically increasing radii (radial increments factor is 1.165), with the first radius corresponding to the probe radius of 1.2 mm, and the last radius corresponding to that of the cylinder of 25 mm. Model elements were named in a AI_K format, where I is the layer number starting from the top, and K is the radial zone number, starting from the center. The temperature probe was assigned at model elements AI_1, where I=1, 2, 3, 4, 5, which corresponds to the depth of the hole on the cylinder sample top (10 mm).

Figure 1: Heater cell with sample.
Figure 2: Laboratory experimental system configuration: 1,2,3,4 – heaters cell numbers, red circles – heaters, grey areas – insulation, crosses – temperature probes.
Figure 3: Cross section of cylinder sample and numerical grid; the hole at the top surface is shown in red.
MODEL PARAMETRIZATION

The known petrophysical parameters in the model include grain density, porosity and permeability. Initial conditions reflect two-phase conditions, with the three primary variables pressure \( P = 10^5 \) Pa, gas saturation (air) \( S_g = 0.9999 \), and temperature \( T \) as measured before heating starts. Heat conductivity \( \lambda \) depends on water saturation according to:

\[
\lambda = \lambda_r + (\lambda_w - \lambda_r) S_w
\]

where \( \lambda_w \) is wet rock heat conductivity, \( \lambda_r \) is dry rock heat conductivity, and \( S_w \) is water saturation.

The heating period is represented by a constant heat generation \( W \) assigned in the external model element B, which is connected to the bottom model elements AA_K (K=1, 2, ... 12) of the cylinder.

There are eleven unknown model parameters to be estimated: \( \lambda_r \) – dry heat conductivity of cylinder sample, \( C_R \) – specific heat of cylinder sample, \( \lambda_i \), \( i = 1, 2, 3, 4 \) – heat conductivities of the insulation covers, \( W_i \), \( i = 1, 2, 3, 4 \) – heater source rates, \( C_p \) – temperature probe heat capacity.

CALIBRATION

In order to reduce the number of unknown parameters to be estimated (heater source rates), a fused quartz QU1 benchmark sample with known properties (Richet, 1982; Sugawara, 1968) was used for experimental system calibration. This benchmark sample is characterized by known heat conductivity (1.38 W/m°C), specific heat (728 kJ/kg °C), and grain density (2210 kg/m³) at 25 °C. QU1 cylinder was made by Tydex JSC with the same size as rock samples, e.g. 50 mm high, 50 mm diameter and 10 mm hole drilled on the top surface.

The QU1 benchmark was inserted in all four cells (4 position test) (Fig. 2). The 4 temperature records obtained in different cells (4 position test) were used as input data for automatic model calibration by iTOUGH2-EOS3 (Finsterle, 1999), which aims to estimate 9 unknown parameters: \( W_i \) (\( i = 1, 2, 3, 4 \) – heat sources in each cell), \( \lambda_i \) (\( i = 1, 2, 3, 4 \) – heat conductivities of each of the insulation covers), and \( C_p \) – temperature probe heat capacity.

This benchmark 4 position test was repeated 3 times (experiments #2011-7-LOG-1, #2011-7-LOG-A-1, #2011-7-LOG-B-1). Although the inversion results show some correlations among the estimated parameters (less than 0.8), the accuracy of the estimates are reasonably good (standard deviations of the estimated parameters are less than a few percents of the parameter value), average temperature residual STD is less than 0.2 °C. Table 1 shows good repeatability of the three estimations based on 12 (3 x 4) temperature records.

<table>
<thead>
<tr>
<th>Estimated parameter</th>
<th>Dimension</th>
<th>Benchmark 4 position tests</th>
<th>Average</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#2011-7-LOG-1</td>
<td>#2011-7-LOG-A-1</td>
<td>#2011-7-LOG-B-1</td>
<td></td>
</tr>
<tr>
<td>( C_p )</td>
<td>W/kg°C</td>
<td>23398</td>
<td>23993</td>
<td>24102</td>
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<tr>
<td>( \lambda_{1,2} )</td>
<td>W/m°C</td>
<td>0.0118</td>
<td>0.0117</td>
<td>0.0118</td>
</tr>
<tr>
<td>( \lambda_{4,2} )</td>
<td>W/m°C</td>
<td>0.0107</td>
<td>0.0109</td>
<td>0.0107</td>
</tr>
<tr>
<td>( \lambda_{4,4} )</td>
<td>W/m°C</td>
<td>0.0105</td>
<td>0.0106</td>
<td>0.0107</td>
</tr>
<tr>
<td>( W_i )</td>
<td>W</td>
<td>6.989</td>
<td>7.057</td>
<td>7.051</td>
</tr>
<tr>
<td>( W_i )</td>
<td>W</td>
<td>6.127</td>
<td>6.253</td>
<td>6.293</td>
</tr>
<tr>
<td>( W_i )</td>
<td>W</td>
<td>5.279</td>
<td>5.289</td>
<td>5.289</td>
</tr>
<tr>
<td>( W_i )</td>
<td>W</td>
<td>5.079</td>
<td>5.118</td>
<td>5.193</td>
</tr>
</tbody>
</table>

After the experimental system was calibrated, additional check inversions were performed with parameters from Table 1 used as known parameters, while QU1 benchmark sample thermal properties \( \lambda_r \) and \( C_R \) are estimated. Table 2 shows good repeatability of the estimates obtained with known QU1 properties (see above).

<table>
<thead>
<tr>
<th>Estimated parameter</th>
<th>Dimension</th>
<th>Benchmark 4 position tests</th>
<th>Average</th>
<th>STD</th>
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<tr>
<td></td>
<td>#2011-8</td>
<td>#2011-8-A</td>
<td>#2011-8-B</td>
<td></td>
</tr>
<tr>
<td>( \lambda_i )</td>
<td>W/m°C</td>
<td>1.396</td>
<td>1.394</td>
<td>1.398</td>
</tr>
<tr>
<td>( C_i )</td>
<td>kJ/kg°C</td>
<td>5729.9</td>
<td>723.8</td>
<td>722</td>
</tr>
</tbody>
</table>

THERMAL PARAMETER ESTIMATION

For this purpose each rock sample was inserted into all four cells of the laboratory experimental system (4 position test) (Fig. 2). Then the 4 temperature records obtained in different cells (4 position test) were used as input data for automatic model calibration by iTOUGH2-EOS3. The number of unknown parameters was reduced after calibration of the experimental system from nine to six: \( \lambda_r \) – dry heat conductivity of rock sample, \( C_R \) – specific heat of rock sample, \( \lambda_i \), \( i = 1, 2, 3, 4 \) – heat conductivities of the insulation covers, which are still considered unknown, because the samples cannot be exactly fit to the insulation covers, i.e., the effectiveness of the insulation may change after sample insulation. Hence, the inversion aims to estimate 6 unknown...
parameters based on 4 temperature records obtained
during “sample 4 positions test”, which was repeated
3 times. Table 3 shows an example of the inversion
results for sample #5. Repeatability and estimates
confidence of tests is rather good, with STD of the
heat conductivity of 0.023 W/m °C and specific heat
of 4.2 kJ/kg °C.

Table 3 Estimates of Sample #5 thermal
properties. Each inversion (#1, #2, #3)
corresponds to sample 4 position test; 
STD – standard deviation.

<table>
<thead>
<tr>
<th>Estimated parameter</th>
<th>Dimension</th>
<th>Sample 4 positions tests</th>
<th>Average</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>λi</td>
<td>W/m°C</td>
<td>1.50 1.46 1.46</td>
<td>1.47</td>
<td>0.023</td>
</tr>
<tr>
<td>Ci</td>
<td>kJ/kg °C</td>
<td>772 764 766</td>
<td>767</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Figure 4 Comparison of the observed (symbols) and calculated (lines) temperatures during “sample 4 positions test” for sample #5.

Although each inversion (corresponding to sample 4 position test) shows correlations among the estimated parameters (less than 0.9), the accuracy of the estimates is reasonable (with standard deviations of the estimated parameters λi and Ci less than a few percents of the estimated values), total temperature residuals STD is less than 0.3 °C. Fig. 4 shows the match between four observed and calculated sets of the temperatures.

THERMAL PROPERTIES OF TRIASSIC VOLCANOGENIC RESERVOIR

iTough2-EOS3 was used to invert for thermal properties of 27 samples collected from the drilling cores of the Rogozhnikovsky oil volcanogenic reservoir. “Sample 4 positions test” was repeated for each of the samples 2 or 3 times, depending on the degree of repeatability results obtained. The quality of the inversion results is equally good for all samples. Figs. 5 and 6 show the estimated thermal properties (heat conductivity and specific heat) plotted against the depth of the sample. The average value of the heat conductivity is 1.47 W/m °C, and that of specific heat is 754 kJ/kg °C.

Figure 5 Heat conductivity vs depth. L – lavas, T – tuffs, B – breccias, L+O – lavas (oil saturated), B+O – breccias (oil saturated).

Breccias are characterized by average values of heat conductivity of 1.51 W/m °C and specific heat of 757 kJ/kg °C (11 samples), lavas – 1.46 W/m °C and 752 kJ/kg °C (10 samples), tuffs – 1.42 W/m °C and 763 kJ/kg °C (6 samples). Comparison of the thermal and hydraulic properties shows that there is some degree of negative correlation (0.28) between heat conductivity and porosity (e.g., heat conductivity decreases with increasing porosity), while other parameters do not reveal any statistically significant dependency.
VERIFICATION AND MATCH WITH THERMAL PROPERTIES OF YUCCA MOUNTAIN TUFFS

A number of different methods used for thermal properties estimation (Clauser et al., 1995; Popov et al., 1999; Fokin et al., 2004). Ten samples from the similar data set of Rogozhnikovsky reservoir were analyzed by optical scanning method (Popov et al., 1999). The average value for heat conductivity is 1.43 W/m °C, and for specific heat is 837 kJ/kg °C. This is close to estimates obtained above.

Tuffs at the potential nuclear waste storage site at Yucca Mountain, Nevada, were extensively studied during the last 30 years (Pruss, 2001). Yucca Mountain consists of multilayered fractured rhyolite tuffs of Neogene age (12.5 M years), characterized by intercalation of thick layers of welded and nonwelded tuffs with low dipping angles (6-7.5 degrees) and complicated by a system of submeridional faults. Welded tuffs have high matrix porosity (0.1), but low matrix permeability (micro-Darcys). Average fracture density is 10 fractures per m³ with fracture permeabilities on the order of 10 D. Nonwelded tuffs have an average matrix porosity of 0.3 and a permeability of 100 mD, and weak fracturing. Thermal properties of these welded tuffs are estimated in the range of 1.12-1.18 W/m °C (heat conductivity) and 851-901 kJ/kg °C (specific heat), while thermal properties of nonwelded tuffs are in the range of 0.36-0.75 W/m °C and 870-1156 kJ/kg °C (Sass et al, 1988).

The values heat conductivities for Yucca Mountain welded tuffs (1.12-1.18 W/m °C) are lower than those for the Rogozhnikovsky reservoir volcanogenic rocks (1.47 W/m °C), while the specific heat of Yucca Mountain welded tuffs (851-905 kJ/kg °C) are larger than those at Rogozhnikovsky (754 kJ/kg °C). This may be explained by rock aging processes.

CONCLUSIONS

1. A method of estimating thermal properties (heat conductivity and specific heat) of the cylindrical rock samples was developed. This method is based on iTOUGH2-EOS3 inversions of the “sample 4 position test” temperature data, collected inside the samples during heating followed by temperature recovery. The accuracy of estimates is a few percents of the estimated values. It is believed that the accuracy of thermal properties estimates may be further improved by increasing the number of positions in the test (Fig. 2), since an “N position test” corresponds to N+2 estimated parameters, hence (number of unknown parameters) / (number of independent observational data sets) decreases as N increases.

2. Thermal parameters of 27 samples collected from the drilling cores of the Rogozhnikovsky oil volcanogenic reservoir were estimated. The average value of heat conductivity is 1.47 W/m °C, and that if specific heat is 754 kJ/kg °C. There seems to be a negative correlation between heat conductivity and porosity.

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