

Laboratory Thermal Rock Properties Measurements of Hard Rock at In-Situ Conditions

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Background

In the field of Geoscience, accurate data on materials' thermal properties is integral in relation to the many processes involving heat transfer and temperature. Such examples where these processes are important include CO₂ storage, nuclear waste storage, and geothermal energy production. Each case has its own challenges, but the fundamental physics underlying the problems are the same. The heat flow is controlled by the thermal conductivity and specific heat capacity of the rock mass (intact rock + fractures). Inaccurate knowledge of these properties could lead to engineering design failure (economics, serviceability, performance, etc). Examples may include under prediction of values, leading to temperature moving faster/further than expected leading to thermal expansion causing fracturing in a CO₂ storage reservoir or nuclear waste repository. Over prediction of thermal conductivity may cause geothermal projects to be overvalued and underperform. In each case, understanding these properties, and the impact of stress and temperature on them, is key to bounding the behaviors of projects controlled by thermal-hydro-mechanical processes.

Researches have shown the impact of uniaxial stress, triaxial stress, and moisture content on the thermal conductivity of rock. For the case of axial stress increases from 0 to 50 MPa, the thermal conductivity may increase up to factor of 2 (Görgülü et al 2008). For changes in confining stress going from 0 to 50 MPa, the thermal conductivity may increase by a factor of 1.5 (Demirci et al 2004).

Methods

Several laboratory methods are available for the determination of properties such as thermal conductivity, specific heat capacity, and thermal expansion. Our Thermal Expansion-Conductivity (TEC40) system builds on the transient divided bar method developed by Demirci et al (2005) and Bording et al (2016) and allows for the simultaneous measurement of thermal conductivity, thermal expansion, and specific heat capacity (**Figure 1**). The testing system is designed to measure the properties at varying levels axial and confining triaxial stress (0-40 MPa), temperatures between -20°C and 200°C, dry rock or 100% saturated, and pore pressures between 0 and 17 MPa. The testing cell sits inside of an environmental chamber and is currently designed to hold cylindrical rock specimens with a maximum diameter of 63.5mm and maximum height of 63.5mm.

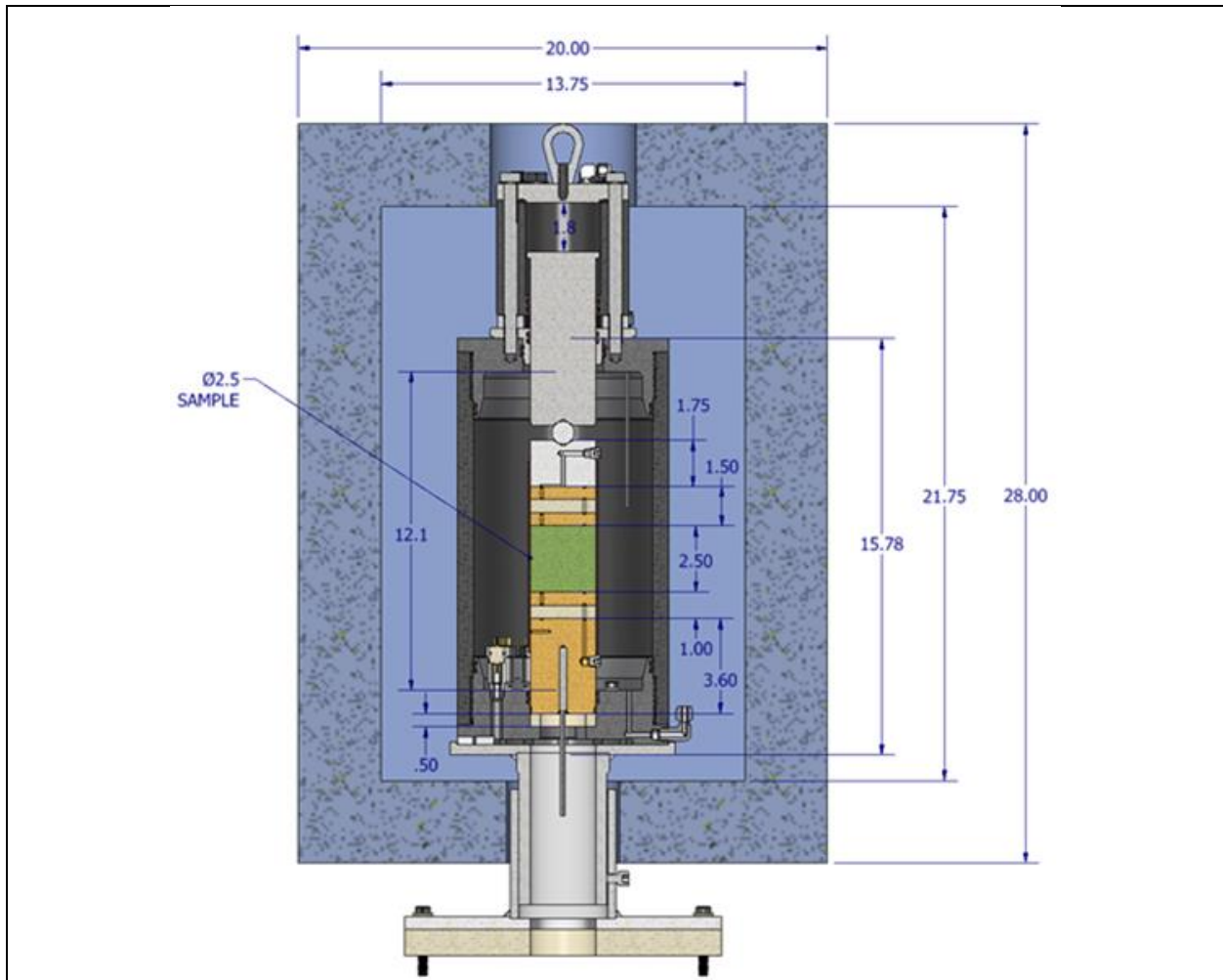
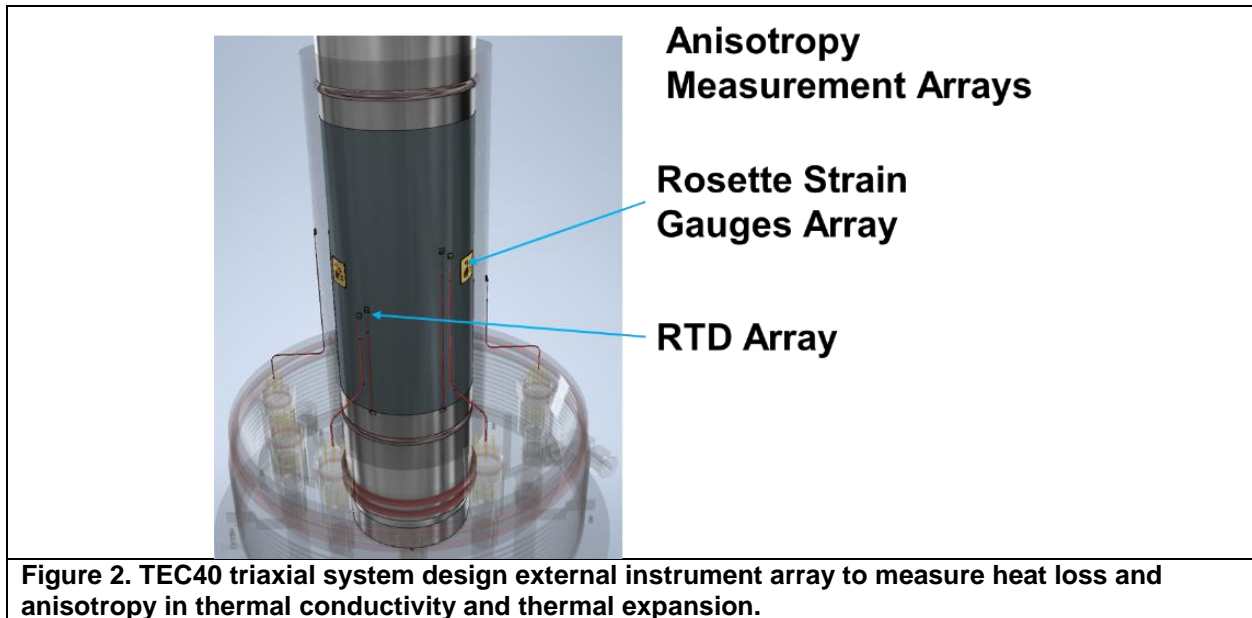
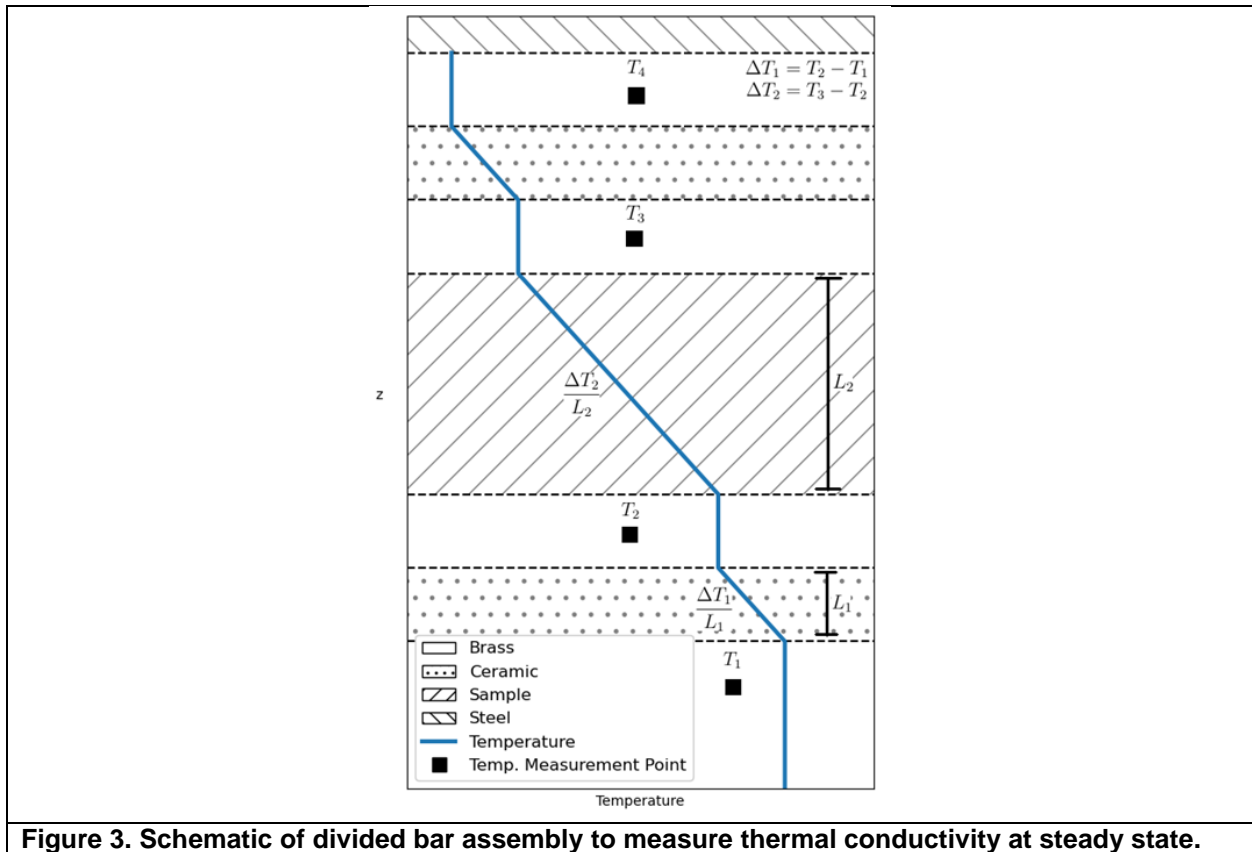


Figure 1. TEC40 triaxial system design capable of measuring thermal conductivity, specific heat capacity, and thermal expansion under confining pressure and axial stress up to 40 MPa and 200degC (dimensions in inches).

The goal of the system is to measure the transient response of the rock to extract the specific heat capacity and the thermal conductivity during a single test while the rock specimen is under triaxial loading. Resistance Temperature Detectors (RTDs) and strain gauge rosettes are implemented to measure the deformation (linear or anisotropy) of the rock as the test temperature or effective stress conditions are varied (**Figure 2**). As the temperature or effective stress is varied, the changes in strain due to each process are used to determine thermal expansion coefficients or the deformation properties (Young's or Bulk modulus). This serves both to measure the thermal expansion properties but also to correct the density of the rock for thermal property measurements.



Constant or variable temperature or power are input to the system and the temperature is monitored with time to extract the thermal properties. The dynamic data can be used to extract the specific heat capacity and the thermal conductivity (Bording et al, 2016) or at steady state the thermal conductivity can be determined (Beck, 1957).



The divided bar steady state solution to measure the thermal conductivity is trivial, however ensuring the system is designed well to efficiently measure the properties of the rock is key. For equilibrium conditions and one-dimensional heat flow, the heat equation reduces to:

$$\frac{d^2T}{dz^2} = 0$$

Where, $T(z)$ is the temperature distribution, and z the distance from the bottom of the material disk. At equilibrium, the heat flux can be assumed constant throughout the system. Hence,

$$\frac{\dot{Q}}{A} = -k_{zirc} \frac{T_2 - T_1}{L_1} = -k_S \frac{T_3 - T_2}{L_2}$$

$\frac{\dot{Q}}{A}$ is the heat flux density, k is the thermal conductivity of the material, which can be solved directly for the desired thermal conductivity k_S

$$k_S = k_{Zirc} \left(\frac{L_2}{L_1} \right) \left(\frac{T_2 - T_1}{T_3 - T_2} \right)$$

Where k_{Zirc} is the known thermal conductivity of the ceramic standard and k_S is thermal conductivity of the sample.

Results, Observations, Conclusions

We are able to overcome past testing systems limitations in saturation levels and temperatures due to our custom built cell which allows for the application of confining pressure, saturation, measurements at temperature, in addition to the commonly applied axial load. The overall system was designed to map as much of the strain and temperature flow as possible.

- A Temperature chamber allows a controlled environment in which to collect data. An intricately designed confining cell, allowing for detailed data collection under further controlled conditions.
- Multiple data collection tools including 14 RTDs, 3 strain gauges rosettes, and 7 pressure transducers, with custom data loggers are implemented to collect data at up to from 0.2 to 100kHz (100 kHz is not required for this testing).
- Multiple pumps and a gas bottle allowing different system components to act at varying pressures using different saturation fluids.
- A conscientiously mapped out system of valves and tubing all mounted on a centralized control board along with other system controllers, easing both test control and surveillance.

The system work will show the initial results from tests to first calibrated and test the system against know materials. Then, testing results on Lac Du Bonet Granite from and Forsmark Granite will be shown. Initially, results for the impact of axial stress ranging from 0 to 20 MPa will be presented.

Novel/Additive Information

Thermal rock properties are generally measured at ambient conditions due to the difficulty in controlling the head loss during testing. At these conditions it is difficult to ensure the rock is saturated or dry as thermal properties are measured at different temperatures. The mechanical design of the TEC40 system allows for the measurements of thermal properties at triaxial effective stress conditions, at 0% saturation or 100% saturation and at temperatures from ambient to 200degC.

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