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# Investigating and predicting permeability variation in thermally cracked dry rocks

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ABSTRACT

Thermal cracking in reservoir rocks can result in significant changes in transport properties. Siltstone, limestone, and conglomerate samples taken from oil-bearing formations were heated to a range of peak temperatures up to 800 °C at ambient pressure. Porosity and gas permeability were measured. Changes in rock microstructures were observed using scanning electron microscopy (SEM). The results show the strong effect of thermal cracking on gas permeability and porosity. Different rock types have different thermal cracking threshold temperatures. Above the threshold temperature, crack widths and lengths are increased and a crack network is well-developed, resulting in sharp variations in gas permeability and porosity. In order to understand the factors that influence both thermal cracking and gas permeability changes in rock, a mathematical model based on fracture mechanics theory and thermoelasticity theory is proposed to describe how permeability changes with increases in temperature. The proposed permeability model was validated using experimental data. The results from the proposed model indicate that thermal cracking and permeability changes are mainly driven by the difference between mineral thermal expansion coefficients. Below the temperature that causes mineral decomposition, the temperature-driven permeability change obtained from the proposed model is in good agreement with our experimental results.

## 1. Introduction

Sedimentary rocks are a composite of multiple minerals. When a sedimentary rock undergoes temperature change, new cracks will be created and/or pre-existing cracks will be activated to reopen and propagate owing to thermal stress. Such thermal stress is caused by differences between mineral thermal expansion coefficients as well as mineral thermal decomposition.[1–3] This process is known as rock thermal cracking or thermal fracturing. The increase in the crack population inside a rock can alter its mechanical and transport properties, including the Poisson's ratio, P- and S-wave velocities, bulk sample density, Young's modulus, permeability, porosity, compressive strength, tensile strength, and fracture toughness.[4–23] Among these properties, permeability is a key parameter controlling the flow capacity of rock. Therefore, understanding and evaluating how rock thermal cracking influences permeability, and how to enhance or avoid permeability variation, are imperative to geoengineering applications such as underground disposal of nuclear waste, geothermal energy extraction, and in situ oil shale retorting.

Extensive experimental studies on rock permeability variation during temperature change have been reported in literature. Somerton et al.[24] used dried cores to investigate the impact of temperature on sandstone permeability, and their experiments revealed that the gas permeability of the rocks increased at least 50% after thermal treatment. Somerton and Gupta[25] further conducted thermal tests on cores saturated with different chemical solutions. The results showed that the chemical solution enhanced rock permeability variation with heating. For example, the permeability of cores saturated with potassium chloride solution showed an 11-fold increase in initial permeability after being heated to 900 °C. However, for the same heating treatment, the permeability of dry cores without potassium chloride solution only increased by a factor of 2.5. This may provide some insight on how to control rock permeability variation during geoengineering. Jamaluddin et al.[26] tested sandstone cores from hydrocarbon reservoirs, and found that the permeability of the cores increased 7.6 times after they were heated to 800 °C. Jones et al.[27] and Chaki et al.[28] also reported that rock permeability increased dramatically when the treatment temperature was above a threshold temperature. Rutqvist et al.[29] tracked the permeability variation of partially saturated and highly fractured volcanic tuff from Yucca Mountain, and they observed that the rock permeability

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of the tuff doubled after a four-year heating and four-year cooling process.

It has been recognised that rock cracking is associated with heating or cooling rates. Richter and Simmons[2] showed that the thermal expansion of unconfined granite heated from 20 °C to 250 °C is fully recoverable for a heating rate of 1 °C/min but not for 5 °C/min, owing to permanent strain remaining after microcracking. Li et al.[30] tested clay shale cores at different heating rates and different confining pressures to evaluate the impact of thermal variation on wellbore and caprock integrities. The maximum temperature was 130 °C for slow heating over five days and 180 °C for fast heating with two cycles of heating-cooling over several hours. They observed that the clay shale sample displayed irreversible deformation in the axial and radial direction under low heating rates, and its structural integrity was maintained (i.e. no fracture or crack was induced). However, under high heating rates, the sample structural integrity was compromised because of tensile fracturing when the thermally induced pore pressure was higher than the tensile strength of the shale. Siratovich et al.[31] heated granite and basalt cores to 375 °C at a confining pressure of up to 35 MPa and rapidly quenched them with cold water to return them to the ambient temperature[32,33]. The observed permeability change was approximately four orders of magnitude higher than the original permeability in these tested samples. Moreover, the increment of rock permeability could have been larger if the temperature was decreased more rapidly after the heating treatment.

Many hypotheses have been proposed in the literature to address the alteration of rock properties by heating. The primary reason for thermal cracking is assumed to be thermal stress. There are several mechanisms that can initiate thermal stress in rocks during heat treatment, including the difference between mineral thermal expansion coefficients, anisotropic thermal expansion of minerals, temperature thresholds, and heterogeneous temperature gradients.[3,16,34–39] Mineral phase change, desorption, and decomposition along with increased temperature can also induce thermal cracking.[40–44] Among these mechanisms, differences between mineral thermal expansion (or contraction) coefficients are known as a primary factor that causes thermal cracking. It can extend and widen existing cracks, and create new inter- and intra-granular cracks. Moreover, both old and new cracks could be further connected to form crack networks, thus changing rock permeability.[3,45]

Microstructure development is an important phenomenon in rock thermal cracking. Scanning electron microscopy (SEM) is a powerful tool to observe microstructural changes, owing to its direct observation of the original sample surface, negligible pollution, strong depth of field, three-dimensional microscopic imagery, and high magnification[46–49]; thus, it has been widely applied to observe crack morphology. Homand-Etienne and Houpert[18] used SEM to investigate the crack development of granite after being heated to different temperatures (20–600 °C). They found that crack width and quantity increased significantly, while crack length remained essentially the same. Géraud[6] observed three microstructures in the thermal cracking process: a transgranular crack network, an intra- and inter-granular tubular crack network, and a mixed crack network. Suzuki et al.[50] immersed granite into 90 °C water for 1000 days, and through SEM imaging found that crack specific surfaces increased and that crack connectivity was improved, resulting in a better crack network. Consequently, the permeability doubled.

Several mathematical models were also proposed to depict the relationship between permeability variation and crack networks. Heuze[51] showed that the permeability of Climax granite increased with temperature by correlating the permeability to the rock's porosity. Palciauskas and Domenico[52,53] and McTigue[54] developed a model to describe the microcrack development within rocks that results from fluid pressure change. It is known that an increase in pore fluid pressure reduces the effective normal stress and consequently enhances shear failure or rock fracturing.[55–59] When fluid is present in poorly connected pores, heating causes a pressure increase in the fluid and enhances the elastic expansion of the solid medium. If the pore pressure is larger than the parting pressure, a crack will be created in the direction perpendicular to the least principal stress. In their thermoelastic model, the Biot isothermal theory was extended into thermal deformation problems to explain the impact of thermal expansion of pore fluids and solid mediums. Le Ravalec and Guéguen[60] built a model to simulate how permeability and connected porosity vary with temperature by combining poroelastic theory and fracture mechanics theory. Their model showed that permeability change was influenced by several factors, including intrinsic permeability, intrinsic connected porosity, crack geometry, rock composition (bulk modulus affecting critical cracking temperature), and temperature. With increasing temperature, pre-existing cracks propagate and new cracks are formed; together, these phenomena generate well-connected crack networks, thus enhancing rock permeability.[61–64]

Our contributions focus on studying the influence of thermal cracking on rock permeability. The primary focus of our study is to predict permeability change in a thermally cracked rock in order to evaluate its transport properties. For this purpose, three specific dry rocks obtained from oil reservoir formations were chosen for heat treatment. First, we perform heat treating experiments to investigate the permeability and porosity changes associated with different temperatures, and use SEM to examine the characterisation of crack morphology in rocks. Then, we propose a mathematical model based on fracture mechanism theory and thermoelasticity theory to predict dry rock permeability variation caused by thermal cracking. Finally, the model is applied to predict permeability change caused by changes in temperature, and its results are compared with the experimental results for these three specific dry rocks.

## 2. Laboratory experiments

The laboratory experiments consisted of two parts. First, the rock samples were heated to different temperatures under atmospheric pressure and then were cooled down to room temperature. After cooling, the permeability and porosity caused by thermal cracking was measured. Second, the samples were imaged using SEM to observe crack development.

### 2.1. Rock material

The rock samples used in the experiments were siltstone, limestone, and conglomerate, which were collected from three heavy oil wells at different stratums in the Shengli oilfield in China. The rocks were cut and milled into cylindrical cores with a diameter of 25.40 ± 0.02 mm for the heat treatment. There were three samples of each type of rock; the key parameters of the core samples are provided in Table 1. The Helium porosity and air permeability were measured using routine core analysis methods specified by the Chinese Oil and Gas Industry Standard (SY/T) 5336-2006. All of the core samples were dried at 100 °C for at least 24 h in a vacuum oven. The porosity was measured using the helium expansion method. Each parameter was measured three times and the average value was taken as the true value. The measurement error was $\pm 0.002 \times 10^{-15}\,m^2$ for permeability and ± 0.03 for porosity.

### 2.2. Methodology

#### 2.2.1. Permeability measurement

Air was used to measure the permeability of the core samples in this study. To eliminate the influence of temperature variation on the permeability tests, the gas permeability measurement system was placed in an air-conditioned room (20 ± 1 °C). The confining pressure was maintained at a constant value throughout an experiment. The pore pressure was maintained at a constant value between 0.1 MPa and