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Temperature dependence of the thermal diffusivity of sandstone

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ABSTRACT

High temperature causes a significant impact on the thermal diffusivity of rocks. The deterioration of the thermal properties of rocks, would seriously threaten many applications in engineering and geosciences, such as petroleum engineering, geothermal energy. This paper emphasizes on the variations of thermal diffusivity of sandstone after high-temperature heating. The results indicate that there are two main reasons for the decrease of thermal diffusivity: the variation of mineralogical composition, the physical and chemical reactions caused by thermal stress. The thermal diffusivity of sandstone decreases with temperature and it tends to be constant once the temperature exceeds a critical value. From 25°C to 300 °C, the decrease is mainly due to the escaping of the adhered water, bound water and structural water. Between 300°C and 600 °C, the thermal response of minerals in sandstone increases the development of microcracks and weakens the thermal diffusivity of sandstone.

1. Introduction

The thermal diffusivity of minerals and rocks at high temperature is an important parameter for understanding the mechanism of the internal dynamics of the earth, the temperature distribution of the earth spheres and the history of the earth's thermal evolution. Meanwhile, studies on the thermal diffusivity of rocks are useful in numerous engineering and scientific applications such as shallow geothermal energy (Fridleifsson, 2001; Kovačević et al., 2013), underground oil or gas transport pipelines (Zhao et al., 1995; Tang, 2013; Hong et al., 2015), nuclear waste repository (Somerton and Gupta, 1965; Kujundžić et al., 2012), underground coal gasification (Maugh, 1977; Wen et al., 2015; Yao et al., 2016), and geothermal energy development techniques (Hofmeister, 2014; Abdulagatov et al., 2015; Verma et al., 2016). The thermal diffusivity of rocks plays a decisive role in geotechnical design, numerical analysis and long-term safety evaluation. A thorough understanding of the geological disasters and the evolution of geological structures therefore requires knowledge about the thermal properties of different rocks that may be encountered in the crust and mantle, under the ambient conditions and at high temperatures. Studying the thermal diffusivity of sandstone is also meaningful for retrieving the earth's evolutionary history and engineering geological research.

Up to date, efforts have been made to measure the thermal diffusivity of materials at temperatures up to 1000 °C (or above) (e.g. quartz, feldspar, pyroxene, olivine and garnet) (Pertermann and Hofmeister, 2006; Branlund and Hofmeister, 2007; Pertermann et al., 2008; Hofmeister and Pertermann., 2008; Hofmeister et al., 2009). Branlund and Hofmeister (2007) studied the lattice thermal diffusivity of eleven orientated natural and synthetic quartz samples and found that the thermal diffusivity of the α-quartz decreases with temperature (i.e. inversely proportional to the temperature) whereas the thermal diffusivity of the β-quartz slightly decreases with temperature or is constant. A sharp decrease of thermal diffusivity marks the α-β quartz phase transition. Hofmeister et al. (2009) analyzed the transport properties of feldspar from the room temperature to high temperatures using the laser-flash analysis (LFA). The thermal diffusivity of feldspar decreases with the increase of temperature, and the thermal diffusivity of the melt is about 15% smaller than the thermal diffusivity of the bulk crystal. However, as one of the most common sedimentary rocks, sandstone was formed after a complex diagenesis in the long-term geological process and it is mainly composed of quartz, feldspar and other lithic fragments. The thermal properties of sandstone vary with the water content, pressure, geological genesis, contents of various mineral constituents as well as internal structures, etc (Shen et al., 1988). Thermal diffusivity as a parameter for evaluating the heat-transformation efficiency in rocks can be influenced by many factors such as structure, water, compositions of minerals, temperature and pressure, which are complex and always interact with each other. Among these factors, temperature is considered to be the most important one because it could induce the occurrences of phenomena such as water escaping, cracks generation (Turner and Taylor, 1991) and minerals

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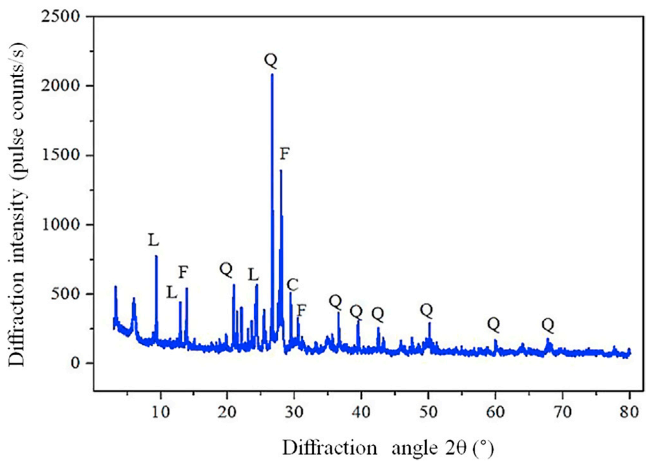

Fig. 1. X-ray Diffraction spectrum of the sandstone sample used for thermal diffusivity measurement. (Q, quartz; F, feldspar; L, limonite; C, calcite).

Table 1
Proximate and ultimate analysis of sandstone in room temperature basis.

SiO_2%	Al_2O_3%	CaO%	MgO%	Fe_2O_3%	Na_2O%	K_2O%	CO_2%
56.04	12.20	7.05	4.17	3.08	2.48	2.02	12.27

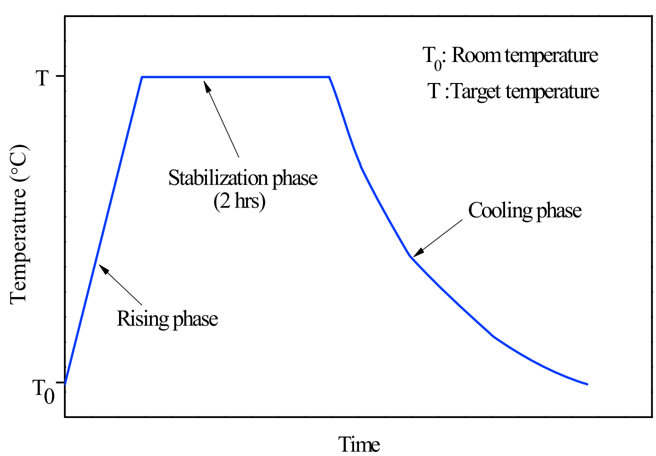

Fig. 2. Heating and cooling regime applied to the sandstone specimen.

transformation. The heat distribution in the earth can also affect the mineral reactions and phase transformation (Buntebarth, 1984) in rocks such as quartz (Heuze, 1983; Branlund and Hofmeister, 2007) and feldspar (Cahill et al., 1992; Hofmeister et al., 2009). Under high temperature conditions, a series of physical and chemical reactions occur in rocks, such as loss of crystal water and structural water, and the decomposition of carbonates in minerals, resulting in varied thermal properties of the rocks with the increase of temperature (Chaki et al., 2008; Zhang et al., 2015). Therefore, the relationship between the thermal diffusivity and temperature has been studied by many researchers (Hanley et al., 1978; Durham et al., 1987; Schilling, 1999; Miao et al., 2014; Sun et al., 2016; etc.). Hanley et al. (1978) studied the thermal diffusivities of eight well-characterized rocks (e.g. Barre Granite, Dresser Basalt, St. Cloud Granodiorite, Westerly Granite, Berea Sandstone, Holston Marble, Salem Limestone, and Sioux Quartzite) in the temperature range of 25–725 °C and found that the thermal diffusivity varies inversely with the temperature and at about 550 °C the value is 50%–75% lower than that at the room temperature. Miao et al. (2014) discerned that the thermal diffusivity and conductivity of granite, granodiorite, gabbro, and garnet amphibolite decrease as the temperature increases, and approach to a constant value at high temperatures. Sun et al. (2016) indicated that the thermal reactions of minerals in sandstone could lead to the reduction of thermal properties. However, the heat transfer mechanism in rocks is complex and few data have been collected on the thermal diffusivity of sandstone at or after being exposed to high temperatures, and the available data are not enough to fully understand the mechanism of the variation of thermal diffusivity with the temperature.

This paper mainly focuses on the variation of the thermal diffusivity of sandstone with the temperature (up to 900 °C). Laboratory tests were conducted for sandstone samples collected in the field, and based on the results of data analysis in this study and previous studies, the thermal expansion and heat of reaction are discussed.

2. Experimental tests and data sources

The investigated sandstone samples were obtained from a borehole drilled at a depth of 780 m in Linyi, Shandong Province, China. The vertical geostress measured in this hole was 21.9 MPa, and the in-situ maximum and minimum horizontal stress were 15.7 MPa and 11.1 MPa, respectively. The mineralogical assemblage of this kind of sandstone was determined by X-ray diffraction spectroscopy (D8 Advance diffractometer; conditions, under the conditions of 45kV/30 mA with Cu Ka radiation, divergence slit 0.6 mm, scattering slit 8 mm, and step width 0.01°). By comparing the X-ray diffraction results of test samples and the sample library of individual matter diffraction patterns,

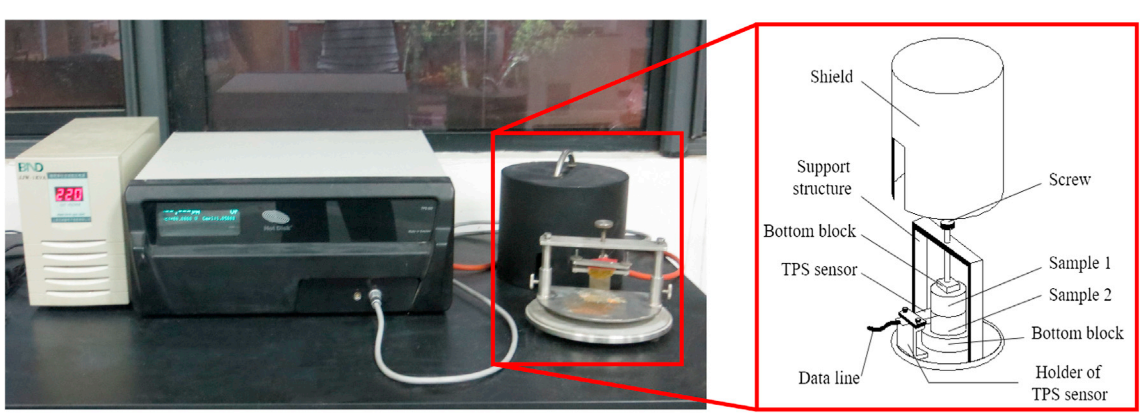

Fig. 3. Hot Disk thermal constants analyzer (TPS 1500) testing system.