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Technical note

Thermal properties of sandstone after treatment at high temperature

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ABSTRACT

This paper reports the variations of thermal conductivity, thermal diffusivity and heat capacity of sandstone after high-temperature heating. Experiments were carried out to test the thermal properties of sandstone which had been heated at temperatures ranging from room temperature to 900 °C in a furnace. Temperature has a significant impact on the thermal conductivity, thermal diffusivity and heat capacity of sandstone, which is closely related to the loss of water and damage of structure caused by thermal reactions. The results indicate four phases in the variation of thermal parameters with temperature: from room temperature to 200 °C, 200–400 °C, 400–600 °C, and above 600 °C. The first and second phases correspond to the vaporization-escaping interval of adhered water, combined water and structural water. Between 400–600 °C, especially from 500–600 °C, the minerals in sandstone has thermal reactions, which are demonstrated as porosity increase, reduction of conductivity and diffusivity, and change of heat capacity.

1. Introduction

The thermal properties of rocks at high temperature or after heating at high temperature produce valuable information for terrestrial sciences, development and solution of applied problems in geothermy, geothermal power generation, and energetics of geodynamic processes of sedimentation basins,[1] geophysics,[2] geological disasters and geological structure formation,[3] such as deep geological repositories for heat-generating radioactive wastes,[4] exploration of geothermal energy,[5–7] deep petroleum boring,[8] exploitation of natural gas[6,9] utilization of hydrothermal energy and underground thermal energy storage, drilling and well logging,[6] and the protection of buildings against fire or building restoration after exposure to fire.[10,11]

In the past few decades, considerable experimental effort has been taken to quantify the relation between thermal properties factor (thermal conductivity, and thermal diffusivity, heat capacity) and temperature of rock. Intense study of the thermal-conductivity factor of rocks began in the middle 20th century in relation to the development of geothermal research aimed mainly at the evaluation of the heat flow rate. The latter is calculated from the measured geothermal gradient in wells and from the thermal conductivity of rocks recovered by them.[12] Somerton and Boozer[13–15] measured thermal diffusivity and conductivity of some typical sedimentary rocks using an unsteady-state conductivity method for 90–800 °C, reporting that thermal diffusivity and conductivity decreased drastically at elevated temperatures. The studies of Vosteen and Schellschmidt,[16] Hanley et al.,[17] Emirov and Ramazanova[1] also show that the thermal conductivity and diffusivity of rocks in general decreases with temperature.

The heat transfer mechanism in rocks is very complex. It is difficult and sometimes impossible to theoretically and correctly predict the thermal conductivity of porous materials, even providing having many simplifications.[2] Rocks are composed by mineral particles with various chemical compositions and different degrees of crystallization. Therefore, the thermal properties of rocks depend not only on the pressure and temperature but also on their mineralogical composition, the structure and geometry of pores, grain sizes, shapes of cracks, and their concentration. Calculation of heat transfer in subsurface of formations requires data on the thermal-expansion characteristics of rock and the heats of reaction of mineral constituents.

Therefore, the research on the thermal properties of sandstone is extremely meaningful on a wide range. In this paper, the variations of porosity and thermal parameters after high-temperature heating (thermal conductivity, thermal diffusivity and heat capacity) are analyzed. Thermal expansions and heats of reaction are discussed in the temperature range of 25–900 °C.

2. Experimental tests

Sandstone samples were obtained from Linyi, Shandong

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province. X-ray diffraction (XRD) analysis showed that the main components of samples are quartz, feldspar, dolomite/ankerite and hematite/magnetite (as shown in Fig. 1), accompanied by a small amount of biotite and kaolinite structure. The highest content of SiO_2 is 35.49%, and the next is CO_2 accounting for 22.64%. The content of CaO, Al_2O_3, MgO, Fe_2O_3 and K_2O/Na_2O are 13.43%, 10.55%, 8.10%, 5.53% and 2.96% respectively. Therefore, the cement of the sandstone is of ferruginous, dolomitic and/or clayey type.

These samples with average bulk density of 2.41 g/cm^3 at room temperature were cut into $\Phi 50\ (\pm 0.05) \times 30\ (\pm 0.05)\ mm^2$ cylinders. The initial content of water was bout 0.07%. In addition to room temperature samples, all the test samples were treated on 100 °C in an oven lasting for an hour before the thermal test. Therefore, there was no adhered water in the tested samples. The heating apparatus consists of a high temperature furnace (type KSL-1100X-L). The specimens used in all the following tests were placed in the furnace and then heated to the designated temperature (25 °C, 50 °C, 100 °C, 150 °C, 200 °C, 250 °C, 300 °C, 350 °C, 400 °C, 450 °C, 500 °C, 550 °C, 600 °C, 650 °C, 700 °C, 750 °C, 800 °C, 850 °C and 900 °C, respectively) at the rate of 30 °C/min. Each specimen was kept at its designated temperature for about 30 min before the power was cut off, and the specimen was allowed to cool down naturally with the decline of temperature in the furnace.

The porosity and thermal parameters of these specimens were tested before and after heating. The porosity was measured by a microporosity structure analyzer apparatus (type 9310) produced by Micromeritics Instrument Corp. The thermal parameters were simultaneously collected with a TPS test machine produced by Hot Disk equipment Co., Ltd.

3. Analysis

3.1. Variation of thermal parameters

The results of thermal conductivity, thermal diffusivity and specific heat capacity are given in Figs. 2–4, respectively. After high-temperature heating, the thermal conductivity, thermal diffusivity and specific heat capacity of sandstone specimens change significantly at the temperature range of 25–900 °C.

From 25 °C to 200 °C, conductivity decreases rapidly with temperature. At the range of 200–400 °C, the thermal conductivity decreases a little bit. However, when the temperature is higher than 450 °C, there is another significant decline range. The greatest rate of decrease in conductivity is at lower temperatures.

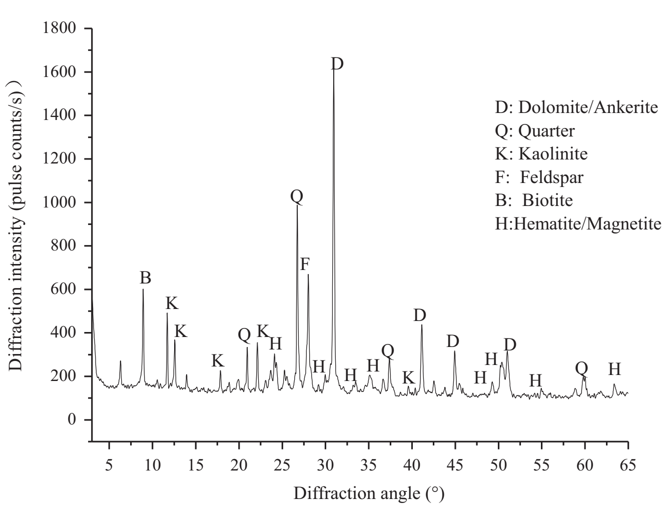

Fig. 1. XRD spectrum of sandstone sample (under 25 °C).

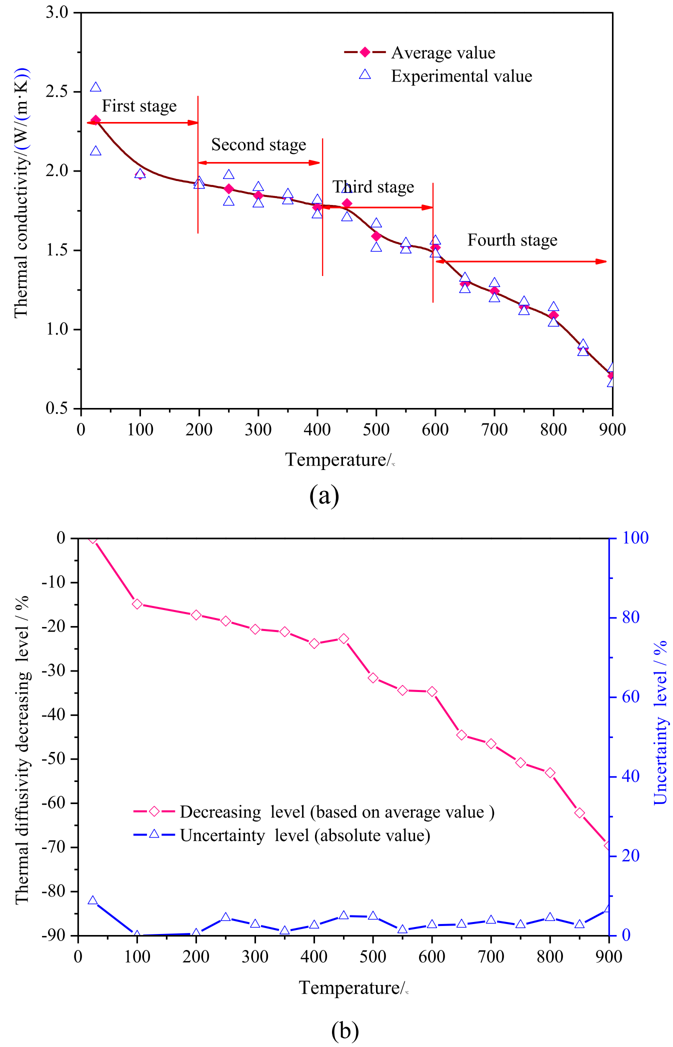

Fig. 2. Variations of thermal conductivity after different temperature treated (a) test results; (b) variation level of thermal conductivity.

From 25 °C to 200 °C, thermal diffusivity decreases rapidly with temperature. At the range of 200–400 °C, the thermal diffusivity decreases a little bit. However, when the temperature is higher than 400 °C, there is another significant decline range. The greatest rate of decrease in conductivity is at the lower temperatures. Above approximately 600 °C, thermal diffusivity becomes essentially constant.

From 25 °C to 200 °C, heat capacity increases rapidly with temperature. At the range of 200–600 °C, there is a volatility for heat capacity, but the whole is relatively stable. However, when the temperature is higher than 600 °C, there is a significant decline range.

3.2. Relationship between porosity and thermal parameters

The variation of total porosity versus temperature is shown in Figs. 5 and 6. Below 400 °C, the porosity changes very little. After that, it increases with temperature. At 600 °C, the porosity is nearly 1.23 times the initial value (under 25 °C). It is reported in literature that most of the mineral grains are micro-cracked at about 400 °C.[18,19] Fig. 5 also shows a plot of porosity under the atmospheric conditions as a function (shown in Eq. (1)) of temperature. The increment of porosity with temperature below 400 °C is small, but becomes significant from that temperature