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Review

Temperature dependence of thermal conductivity, diffusion and specific heat capacity for coal and rocks from coalfield

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ABSTRACT

The thermal properties of coal and rocks play an important role in the development of coalfield fires, head flow and the inversion of temperature. In this study, the thermal diffusivity and specific heat capacity were measured for bituminous coal from 25 to 300 °C, and sandstone and granite from 25 to 1000 °C using the laser-flash apparatus LFA457. The samples were taken from the Wuda coalfield. Combined with density data, thermal conductivities were then calculated. The results suggest that the method is able to accurately determine thermophysical properties for rocks in the temperature range of Earth's deep interior. When the temperature increases, thermal diffusivity and thermal conductivity decrease, and the decreasing thermal conductivities are generally linear. At high temperatures, thermal diffusivity and thermal conductivity approach constant values.

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1. Introduction

Thermal conductivity, diffusivity, and specific heat capacity are the rock and coal properties that are necessary in determining temperature of the interior of the Earth. Subsurface temperature also affects rheology of Earth materials and virtually all geochemical processes. Therefore it is important to know the variations of thermal conductivity, diffusivity, and specific heat capacity between and among various rocks and coals so as to understand the thermal state and evolution of Earth's interior [1]. Temperature plays the most important role among various factors which affect the thermophysical properties in the Earth's crust [2]. Accurate and simultaneous measurements for any two of these parameters (thermal diffusivity D, specific heat C_p, and thermal conductivity λ) are needed, and there is lack of data in literature for the Wuda coalfield. This information is also helpful in determining when a coalfield fire occurs and the course of its development. The thermal properties are important in understanding how coalfield fires spread as well as the exchange of energy through combustion, fracture porosity, and also provide basic data for simulations of the coalfield fire process.

Material thermal conductivities depend not only on temperature but also pressure. For most geological materials, thermal conductivity decreases up to 40–60% of the original value when the temperature increases from room temperature to 1273 K. When the pressure increases by 1 GPa, the thermal conductivity increases by

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approximately 4% of the ambient pressure value [3]. For crustal rocks, the maximum temperature can be 1073 K, and the pressure is typically below 1.5 GPa [4]. Therefore, the pressure effects on thermal conductivity can be neglected, and thermal conductivity measured under high temperatures and normal pressure represents realistic thermal conductivity under crustal conditions. Compared with the few methods for thermal conductivity measurements at high temperatures and high pressures, more methods are available for measurements under normal pressure and high temperatures conditions. Among such methods, the laser-flash technique is preferred [5]; it is a non-contact method that avoids the inevitable thermal contact resistance of traditional contact methods. Moreover, the graphite and silver film coating on the sample surface can prohibit direct radiated heat transfer. Therefore, the real lattice thermal conductivity for samples can be derived. This method directly measures thermal diffusivity for samples and calculates thermal conductivity through the sample's specific heat capacity and density. Because sample thickness is the only parameter involved, this method is highly precise, with a 3% nominal error [6]. Detailed studies have been performed for certain common minerals using this method (e.g., quartz, feldspar, pyroxene, olivine, and garnet) [7–11], and the temperature dependence of the thermal diffusivity for such minerals is understood. Whittington et al. [12] determined thermal diffusivity for granite and rhyolite at a high temperature using the laser-flash technique. More recently, basalt, granulite, greenstone, tonalite–trondhjemite–granodiorite, dolomite, and rhyolite glasses have been measured using the laser-flash technique [13–16].

Many researchers have measured the thermophysical properties of coal and rocks mainly in normal conditions, but few data is available at high temperature especially for coalfields. It is necessary to study the effective thermal conductivity, thermal diffusivity and specific heat capacity influenced by temperature for the coalfield samples. The main purposes of this study are: (1) to provide accurate experimental data for geological porous materials using the laser flash method (bituminous coal from 25 to 300 °C, sandstone and granite from 25 to 1000 °C); (2) to study the effects of temperature on thermal conductivity, diffusivity and specific heat capacity of coal and rocks.

2. Experiment

The system has three main parts: the laser heating system, high temperature furnace, and temperature detector. The NETZSCH LFA 457 MicroFlash® is based on the well-established flash method [17]. The uncertainty accuracy for this machine of thermal diffusivity is ±3% (for most materials) and specific heat capacity is ±5% (for most materials) [5]. The lower surface of a parallel plane of the sample is first heated by a short energy pulse during a measurement. The absorbed heat that is induced then propagates through the sample and causes a temperature increase on the rear surface. The resulting temperature change on the surface is then measured versus time with an infrared detector. The higher the sample's thermal diffusivity is, the steeper increase of the signal is. If the density (ρ) is known, using the half time ($t_{1/2}$ time value at half signal height) and the sample thickness (d), the thermal diffusivity (D) and the thermal conductivity (λ) can then be calculated by means of formula (1). Furthermore, the specific heat (c_p) of solids can be determined using the signal height ($\Delta T_{\max}$) compared to the signal height of a reference material. In the earth's lithosphere, conduction of heat generally dominates among other mechanisms as radiation and advection. Ignoring the density change associated with thermal expansion, thermal conductivity can be calculated by:

$$\lambda(T) = D(T) \cdot \rho(T) \cdot c_p(T) \quad (1)$$

Table 1
Proximate analysis of bituminous coal.

Property	Bituminous coal
Volatile matter (wt% daf)	32.49
Ash (wt% dry basis)	6.70
Moisture (wt%)	8.03

where D is the thermal diffusivity, ρ is the density, c_p is the specific heat capacity, λ is the thermal conductivity, and T is the temperature in K.

The profiles of the thermograms and the subsequent analysis according to Parker's method are reported. Parker and Jenkins [18] has solved the heat equation restricted to one dimension, and in the total absence of heat exchange between the sample and the furnace atmosphere and with a Dirac-like laser pulse, it can be expressed as:

$$D = \frac{\gamma L^2}{t_{1/2}} \quad (2)$$

where D is the thermal diffusivity of the material, L the thickness of the sample, $t_{1/2}$ the moment when the temperature rise is half of the maximum and $\gamma \approx 0.13878$. When the heat losses by the front and rear faces of the disc are considered, Cowan [19,20] has shown that the previous equation can be used, but γ is no longer a constant: it can be obtained from a graph as a multiple of 5, the ratio of the temperature rise at $5^* t_{1/2}$ to the maximum amplitude.

Bulk samples were taken from the Wuda coalfield fire area. The parameters of proximate and ultimate analysis for bituminous coal are shown in Tables 1 and 2. The density of the samples at 20.0 °C are 1.111 g/cm^3 for the bituminous coal, 2.343 g/cm^3 for the sandstone, and 2.043 g/cm^3 for the granite. The bulk samples were cut into disks by means of an impregnated diamond-slitting disk. After slitting, the sample faces was polished and lapped parallel. The samples were prepared in the shape of disks with 12.70 mm diameter and 2.50 mm thickness to be suitable for the thermal diffusivity measurement. The upper and lower disk surfaces were coated with graphite and silver film. This process inhibits direct radiative transfer at high temperatures and promotes laser heat absorption at the lower surface. The graphite–silver coating was 20 μm thick; thus, it did not affect the measurement results. After the sample was positioned, the furnace was vacuumed and filled with inert argon gas. With a 20 K/min heating rate, measurement began when the temperature reached a particular value and remained stable. During the measurement process, the maximum temperature increase inside the sample associated with the laser pulse was less than 3 °C. Therefore, the thermal diffusivity measured was for the preset furnace temperature.

The experiment was carried out under vacuum conditions at room temperature, and the experimental furnace was initially filled with atmosphere. The experimental thermal properties of coal were calculated using the model proposed by Cape et al. [21] and the thermal properties of rocks were calculated by the model proposed by Cowan [20].

3. Result and discussion

3.1. Thermal diffusivity

The temperature dependence of the thermal diffusivities was measured for the temperature ranges from room temperature to 300 °C for the bituminous coal, and from 25 to 1000 °C for sandstone and granite (Fig. 1a). The thermal diffusivities were fitted to the Eq. (3), using the model proposed by Mostafa et al. [22].

$$D = \frac{1}{(A + BT)} \quad (3)$$

where A and B are fitting parameters (Table 3).