

Effect of mineral matter on coal self-heating rate

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Abstract

Adiabatic self-heating tests have been conducted on subbituminous coal cores from the same seam profile, which cover a mineral matter content range of 11.2–71.1%. In all cases the heat release rate does not conform to an Arrhenius kinetic model, but can best be described by a third order polynomial. Assessment of the theoretical heat sink effect of the mineral matter in each of the tests reveals that the coal is less reactive than predicted using a simple energy conservation equation. There is an additional effect of the mineral matter in these cases that cannot be explained by heat sink alone. The disseminated mineral matter in the coal is therefore inhibiting the oxidation reaction due to physicochemical effects.

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1. Introduction

Coal self-heating, leading to spontaneous ignition, continues to be a hazard that must be managed by coal mines to create a safe work environment [1]. Spontaneous combustion management plans (SCMPs) should contain data that can be used to assess the inherent propensity of the coal to self-heat. This usually involves obtaining results from small-scale laboratory tests. One such test that is frequently used by the Australian coal industry is the adiabatic oven R_{70} self-heating rate test, which can also be used to study and quantify the factors that affect coal inherent self-heating propensity [2–6]. The test measures the average self-heating rate between 40 °C and 70 °C, known as the R_{70} self-heating rate index [7]. The higher the R_{70} value, the higher the propensity of coal for self-heating. Tests of this genre have been criticized in the past on the grounds that they disregard different thermal diffusivities of the coals tested. These tests also provide a full temperature history of the self-heating process through to

thermal runaway at temperatures up to 160 °C and the data can be used to define the reactivity of coal.

One important factor that affects coal reactivity and hence self-heating propensity is the mineral matter content of the coal. However, little is known about mineral matter effects on coal self-heating, other than brief investigations by Humphreys et al. [7], Smith et al. [8] and Beamish and Blazak [4]. Smith et al. [8] looked at the heat sink effect of adding different minerals and inorganic constituents to coal as a possible solution to inhibiting coal self-heating. Humphreys et al. [7] added differing amounts of coal ash to the same coal sample to test a mineral matter free correction equation for the R_{70} self-heating rate. Beamish and Blazak [4] and Beamish et al. [9] showed a strong negative correlation exists between ash content and R_{70} self-heating rate of both low and high rank coals. Such a relationship is not accounted for in most models of coal spontaneous combustion.

This paper presents a more detailed kinetic analysis of the self-heating rate data obtained by Beamish and Blazak [4] from subbituminous coal cores. The effects of mineral matter in the coal are clearly defined by means of mathematical modelling of the heat sink effect over the entire

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temperature range of the adiabatic oven test from 40 to 160 °C.

2. Experimental

2.1. Coal samples

The coal samples used in this study were obtained from a geotechnical drilling program in the Callide Basin, Queensland. The cores selected for testing came from the one borehole and were thus of the same rank suite of samples. To maintain sample integrity, all cores were firstly wrapped in plastic cling wrap then aluminium foil and finally an outer layer of masking tape, before being chilled on ice at the drill site. These samples were then transported to the laboratory in an insulated container full of ice and transferred immediately to a freezer for storage until adiabatic testing was performed. Four samples from the original suite tested by Beamish and Blazak [4] are considered in this study. These are TG1, TG2, TG5 and TG6. Coal quality data for the samples are given in Table 1. The coal is classified as subbituminous A in rank, with the low volatile matter contents being a reflection of the high inertinite content of the Callide coal [10]. X-ray powder diffraction analysis of the samples identified kaolinite as the predominant mineral present in the coal, with subordinate amounts of quartz and siderite.

2.2. Adiabatic oven tests

Full details of the adiabatic oven used for the self-heating experiments are given in Beamish et al. [2]. Each sample was crushed to <212 μm just before testing in the adiabatic oven to minimise the effects of oxidation on fresh surfaces created by the grinding of the coal. A 150 g sample of the crushed coal was dried under nitrogen at 110 °C for ~16 h to ensure complete drying of the sample. Once drying was complete, the coal was allowed to cool down to 40 °C before being placed into the reaction vessel and transferred to the adiabatic oven where it was allowed to equilibrate at a temperature of 40 °C under nitrogen. When the sample temperature had stabilised, the oven was switched to remote monitoring mode. This enabled the oven to track the coal temperature rise due to oxidation.

Table 1
Coal quality and parameters used for adiabatic testing

| Sample | TG5 | TG6 | TG1 | TG2 |
|-----------------------------------|-------|-------|-------|-------|
| Total test mass (g) | 150.3 | 150.1 | 150.2 | 150.2 |
| Moisture removed (g) | 21.4 | 17.9 | 18.4 | 13.5 |
| Dried reactant mass (g) | 128.9 | 132.2 | 131.8 | 136.7 |
| Mineral matter mass (g) | 14.4 | 41.6 | 59.0 | 97.2 |
| Mineral matter free coal mass (g) | 114.5 | 90.6 | 72.8 | 39.5 |
| Moisture (% ar) | 14.2 | 11.9 | 12.3 | 9.0 |
| Mineral matter (% db) | 11.2 | 31.5 | 44.8 | 71.1 |
| Ash (% db) | 9.8 | 28.4 | 39.1 | 62.2 |
| MM/ash | 1.14 | 1.11 | 1.15 | 1.14 |
| Volatile matter (% dmmf) | 27.2 | 27.7 | 27.8 | 28.0 |
| Fixed carbon (% dmmf) | 72.8 | 72.3 | 72.2 | 72.0 |

The gas selection switch was turned to oxygen with a constant flow rate of 50 mL min⁻¹. The temperature change of the coal with time was recorded by a data logging system for later analysis. It was assumed sensible heat removal by the gas is insufficient to affect the combustion phenomenology. The oven limit switch was set at 160 °C to cut off the power to the oven heating element and stop the oxygen flowing when the sample reached this temperature.

2.3. Evaluation of adiabatic oven tests

In an adiabatic oven, it is assumed that an ideal adiabatic condition for the sample is created. It means that all the heat produced by coal oxidation is used for heating of the coal sample. A simplified energy conservation equation for the coal sample in the adiabatic oven can be written in this case. This ignores finite convective and diffusive heat transfer rates and heat given to the incoming gas flow and also ignores reactant depletion. Dry coal is considered to consist of two constituents, namely mineral matter free coal (mmfc) and mineral matter (mm). Mineral matter free coal reacts with oxygen and releases heat of reaction, meanwhile mineral matter does not react (unless it is finely disseminated pyrite [8]) and has no contribution to the oxidation reaction between carbon and oxygen. The energy conservation equation for coal in the reaction flask can be written as follows:

$$(m_{mm} \cdot C_{p,mm} + m_{mmfc} \cdot C_{p,mmfc}) dT/dt = V_{mmfc} \cdot q_{ox,mmfc}^0 \quad (1)$$

where $q_{ox,mmfc}^0$ = heat release rate of reaction in oxygen atmosphere during adiabatic oven testing [W m⁻³], V_{mmfc} = volume of mineral matter free coal in the sample [m³], m_{mm} and m_{mmfc} = mass of mineral matter and mineral matter free coal respectively [kg], $C_{p,mm}$ and $C_{p,mmfc}$ = specific heat of mineral matter and mineral matter free coal respectively [J kg⁻¹ K⁻¹].

$$m_{mm} = m_{coal} \cdot R_{mm}$$

$$m_{mmfc} = m_{coal} \cdot (1 - R_{mm})$$

$$V_{mmfc} = m_{mmfc} / \rho_{mmfc} = m_{coal} \cdot (1 - R_{mm}) / \rho_{mmfc}$$

where R_{mm} is the ratio of mineral matter in dry coal. Inserting these equations into Eq. (1) results in the heat release rate of coal being defined as follows:

$$q_{ox,mmfc}^0 = [\rho_{mmfc} \cdot (R_{mm} \cdot C_{p,mm} + (1 - R_{mm}) \cdot C_{p,mmfc}) / (1 - R_{mm})] dT/dt \quad (2a)$$

or

$$q_{ox,mmfc}^0 = \rho_{mmfc} \cdot C_p \cdot dT/dt \quad (2b)$$

where $C_p = (R_{mm} \cdot C_{p,mm} + (1 - R_{mm}) \cdot C_{p,mmfc}) / (1 - R_{mm})$.

2.4. Non-Arrhenius rate data from adiabatic oven tests

Data files from the adiabatic oven tests contain temperature values of the coal sample from 40 °C up to approxi-

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