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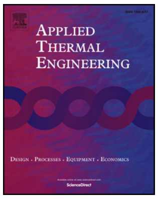

Research Paper

A lab-scale experiment on low-temperature coal oxidation in context of underground coal fires

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HIGHLIGHTS

- A lab-scale experimental setup to simulate underground coal fires is established.
- Natural convection of air is the primary driving force for the chemical reactions.
- Temporal variation of surface thermal anomaly and CO/CO_2 emissions are studied.
- Correlations between the coal temperature and other parameters are identified.

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ABSTRACT

Underground coal fires (UCFs) cause remarkable loss of energy resources and significant environmental pollution. Understanding the fundamental characteristics of low-temperature oxidation of coal is related to the prevention and detection of UCFs. A lab-scale experimental setup is designed and built to study the coal spontaneous combustion under the natural convection of air into the coal layer. Alumina porous ceramic blocks with through-cuts are employed to simulate the overburden above the coal seam. Temporal variation of coal temperature, exhaust gases temperature and volumetric fractions of CO and CO_2 are measured and analyzed. In addition, the thermal anomaly on the overburden surface is monitored, and its correlation with the underneath coal temperature is identified. It is found that air supply is the primary limiting factor that dictates the intensity of coal-oxygen reactions, and the ratio of CO_2/CO in the exhaust gases exhibits a strong dependence on the regime of coal-oxygen reactions.

1. Introduction

Underground coal fires (UCFs) pose serious threats to energy resources, environment, human health and mining safety, very common in most coal-producing countries including China, the United States, India, Indonesia and others [1,2]. At the early stage of UCFs, they are usually very difficult to be detected, while once found, the fires are extremely difficult to be completely extinguished [3]. By tracking the surface thermal anomalies, remote sensing is a very powerful and economical tool for early detection of UCFs because of its low cost and wide availability [4,5].

The physio-chemical processes between the coal and oxygen during the low-temperature stage are very complicated. Physical and chemical adsorption occur first, followed by oxidizing reactions between the functional groups and oxygen at higher temperatures. Pyrolysis is another process which includes dehydration and release of volatiles. The physical and chemical adsorption as well as the oxidizing reactions are exothermic, while the pyrolysis is endothermic. Low-temperature oxidation of coal and its reaction kinetics under various conditions have been extensively studied [6–19]. In their experiments and analyses, forced air flows are directed to pass through the isothermal [6–13] or adiabatic [14–16] reactors piled with coal particles. Gas emissions at the exit are collected and analyzed to identify the reaction paths and to derive the reaction mechanisms. Besides coal properties, other factors include the oxygen content, air flow rate, reactor temperature and particle size. However, the dominant driving force in most UCFs is natural convection caused by the density difference between the air and exhaust gases. Hence, the above-mentioned studies are more relevant to coal mine fires in which forced ventilation is present [20].

Because UCFs usually occur in large-scale coal fields, there exists a

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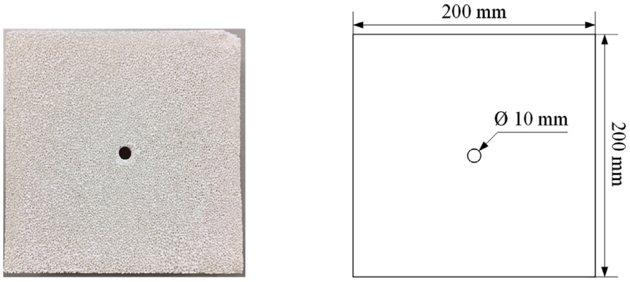
strong coupling of many factors such as the geological conditions of the overburden, direction and depth of the coal seam, coal properties, ambient temperature, precipitation and so on. Efforts have been made to develop multi-physics models to investigate self-ignition and reaction front propagation in UCFs [21–26]. More advanced models that incorporate geological mechanics were developed to consider the deformation and subsidence of the roof rocks [27,28]. The difficulty of modelling UCFs lies in the accurate determination of many physical properties, for example, the thermal conductivity and the permeability of the overburden.

The objective of this study is to develop a lab-scale experimental setup which comprises most essential elements of the large-scale UCFs. Since UCFs are a result of the self-ignition of coal in a semi-open environment, the experimental system must include the overburden to account for the seepage flows of air and exhaust gases. In addition, natural convection of air should be enabled in the experiment. The focus of the present study is placed on the low-temperature oxidation of coal, that is, the early stage of spontaneous combustion, because of its relevance to early detection and prevention of UCFs. The goal of the present study is to acquire fundamental characteristics of low-temperature oxidation of coal in the context of UCFs, including the temporal variation of coal temperature, exhaust gases temperature and CO and CO_2 volumetric fractions.

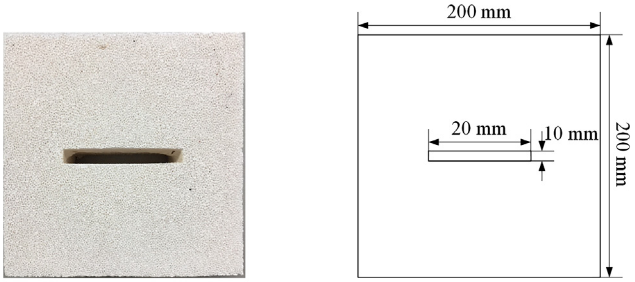
2. Experiment

2.1. Experimental setup

The occurrence and development of UCFs are mainly controlled by heat and mass transport in the geological and ambient environment. Fig. 1 schematically shows the heat and mass transport in a typical UCF. It is not practical to use soil or rock to simulate the overburden because their properties vary a lot and it is difficult to characterize them. For example, the permeability is a strong function of piling method, which incurs a lot of uncertainty to the experiment and the reproducibility cannot be guaranteed. The overburden properties actually appear in the mathematical governing equations twice, they are, the thermal conductivity in the energy equation and the permeability in the momentum equation. Alumina porous ceramic with 50 PPI (pores per inch) is finally chosen because it is able to withstand high temperature without degradation. Moreover, its properties like porosity can be easily controlled in the process of manufacturing. Another requirement for most UCFs is open fractures for the flows of air or exhaust gases. To meet that requirement, open fractures need to be fabricated. Two types of fractures are adopted, one is designated as 'point-fracture', and the other 'line-fracture'. Their detailed dimensions and direct pictures are illustrated in Fig. 2. It is acknowledged that those fractures significantly deviate from actual conditions which usually take very complicated geometries or orientations, but they offer at least two significant advantages. Firstly, a good consistency (dimension, shape an orientation) can be ensured for various experimental cases. Secondly, those fractures are much easier to be implemented in numerical models afterwards.



Point-fracture



Line-fracture

Fig. 2. Illustration of alumina porous ceramic blocks with open fractures.

Fig. 3 shows the schematic of the experimental setup. A reaction tank made of stainless steel 316 is the main body. It has the dimensions of 200 mm (L), 200 mm (W) and 350 mm (H). Thermal insulation is employed to minimize heat losses from the side and bottom walls of the reaction tank. Inside the tank, from the bottom to the top, they are: (1) an electric heater; (2) a layer of coal particles; and (3) alumina porous ceramic. The purpose of applying the electric heater is to shorten the time needed to reach the self-ignition state. Five OMEGA® K-type thermocouple probes are used to monitor the temperature in the coal layer, denoted as TC1 to TC5. The temperature data are collected by an AGILENT® (Model: 34972A) data acquisition unit. The temperature and volumetric fractions of CO and CO_2 of the exhaust gases are measured by a TESTO® (Model: 350) gas analyzer by placing the gas sensor at the exit of the fracture. The surface temperature of the alumina porous ceramic is captured by a FLUKE® (Model: Ti400) infrared thermal

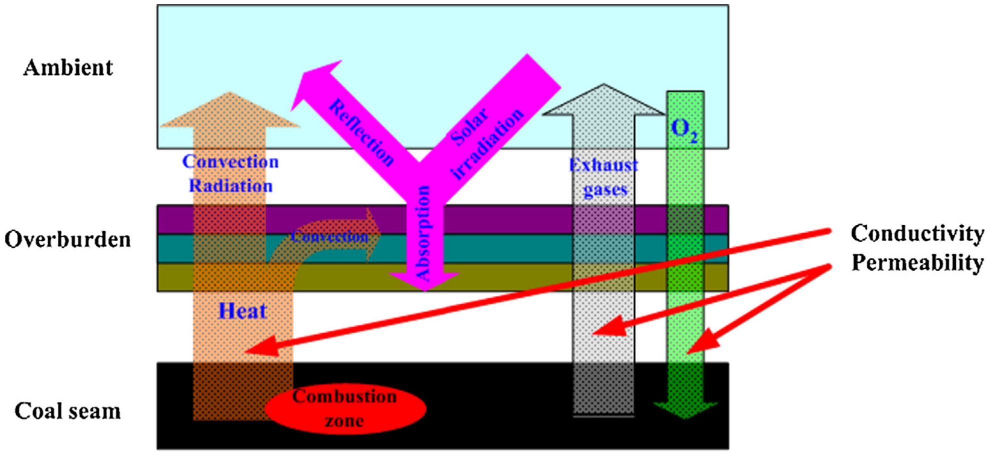


Fig. 1. Schematic representation of heat and mass transport in underground coal fires.