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Monitoring of coal fracturing in underground coal gasification by acoustic emission techniques

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HIGHLIGHTS

- Assessing a novel monitoring method (acoustic emission) for underground coal gasification.
- Real-time monitoring of the fracturing and cavity growth during UCG process.
- Clarifying the correlation between AE activities and local-temperature variations in the gasification zone.
- Developing a crack distribution model to visualize the fracturing behavior in UCG.

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ABSTRACT

During the underground coal gasification (UCG) process, fracturing and cracks occur inside the gasification zone and surrounding rocks as the underground coal cavity evolves. Although fracturing activity and crack extension directly affect gasification efficiency and have environmental impacts, little research to date has focused on their effects. This study discusses the application of acoustic emission (AE) analysis for the evaluation of distinctly designed UCG models and operational parameters and describes the gasification process based on its results. We studied the cavity growth, fracturing mechanism, and the effects of various design and operational variables, such as linking-hole type, gas feed rate, and gasification agent. We found that the AE activity was closely related to the temperature change occurring inside the coal, with AE generation apparently resulting from crack initiation and extension around the coal gasification area, which occurs as a result of thermal stress. UCG modeling showed that the location of AE sources reflects the size of the gasification area and the cavity growth. In addition, the quantitative information on the located AE sources can be obtained. The introduction of a process control system into UCG modeling along with AE monitoring allowed for the real-time monitoring of the fracturing and cavity evolution inside a combustion reactor. Together, these processes have the potential to significantly reduce field risk in UCG by enabling the timely adjustment of operational parameters. Thus, AE monitoring is useful for maintaining a safe and efficient UCG process.

1. Introduction

Fossil fuels remain the primary energy source worldwide, and coal, the most abundant fossil fuel source, is responsible for providing a high percentage of electricity generation. Most power plants still use combustion processes [1,2] and are responsible for the emission of stationary-source carbon into the air. As the largest developing countries with maximal coal yield and consumption, China and India use coal as their primary energy source. In particular, considering the amount of coal in India and its high ash content (13.5%–50%), low calorific value, and seam depth, there is a distinct need to make better use of these resources [3,4]. Increasingly serious climate and environmental problems have also spurred interest in research on the development of clean and efficient coal technologies. Underground coal gasification

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(UCG) is a promising environmentally acceptable technique for the utilizing coal reserves, particularly those at great depths or under complicated geological conditions that are unmineable or uneconomic with conventional production methods [5–12]. UCG involves the gasification of coal within the seam via a process of injecting oxidants through an injection well and extracting the resulting syngas through a production well. This process has only a modest environmental impact and produces an easily transportable product that can serve as fuel gas or chemical feedstock or be used for liquid fuel production [13,14]. In some cases of deep coal seam, many UCG operations also create by-product of CO_2 suitable for developing an UCG-CCS (carbon capture and sequestration) system with the technological development of CO_2 capture and storage [5,10,15–18]. Hydrogen production from underground coal gasification has also been pursued in recent years [19–22]. UCG has several advantages over surface coal gasification, including cost efficiency, elimination of ash waste, and provides the potential site (cavity formed in underground) for carbon sequestration [8,23].

The idea of UCG was first proposed by Sir William Siemens in 1868 [24] as a means of solving the problems of smoke pollution in industrial cities. Instead of burning coal at the surface, he suggested placing a conventional surface coal gasifier into a mine and gasifying waste and slack coal underground. Two decades later, Dimitri I. Mendeleev noted that gasifying coal *in situ* could potentially lower cost inputs (less equipment for excavation), improve labor safety (with no underground labor required), and allow for more convenient transportation (gas pipeline transport) than traditional mining [25,26]. In 1910, an American engineer Anson G. Betts who was granted three patents for inventing a method of gasifying the unmined coal and considered the effect of various important factors on *in situ* coal gasification [27–29]. Jolley et al. reported early experimental attempts to the underground coal gasification [30–32].

Owing to these significant advantages, UCG has been attempted in many countries through laboratory-scale experiments and field tests [33–36,21,37–42], and was even applied in the USSR for industrial scale power production [5]. Recently, research on UCG has gained increasing attention [43–47] and many remarkable modeling investigations were conducted for investigating various effects on gasification efficiency, flame propagation, coal consumption, etc. However, the process incurs potential risks in the form of surface gas leakage, groundwater contamination, and surface depression as a result of improper UCG operation or other unpredictable factors, as coal spalling and the evolution of the underground cavity causes changes to the target coal seam and surrounding rock layers. In the 1970s and 1980s, dozens of UCG trials were performed in the U.S.; three of these tests (Hoe Creek I, II, and III) at Hoe Creek, Wyoming [48–51] produced water contamination and subsidence that were possibly caused by overpressurization and excess fracturing in the gasification area. Environmental risk assessments require the consideration of cracking under high cavity temperatures, cavity growth, and the fracture mechanism during and after the UCG process. There is little information available in literature about the fracturing activities involving crack initiation and extension around underground gasifier during the UCG process. Therefore, a precise evaluation of the combustion area of the underground coal seam is necessary. In particular, monitoring of fracture activity in the coal seam and surrounding rock is important not only for efficient gas production but also for the estimation of subsidence, pollution of underground aquifers, and gas leakage to the surface. The creation of a combustion reactor in an underground coal seam during the UCG process involves the flow of oxygen and other gases through an injection well and the collection of heat energy and gases from a production well. As gasification progresses, the combustion reactor is moved along the linking hole. In this process, the fracturing activity inside the coal seam serves an important role in enlarging the gasification zone through a process of continuous surface area oxidization caused by coal cracking. For effective coal gasification, this fracturing activity must be controlled. Moreover, excess fractures inside the coal seam and surrounding rock can induce cavity collapse, subsidence, contamination of local freshwater aquifers, etc. Therefore, monitoring and controlling of fracturing activity in underground areas are key technological requirements for efficient and safe UCG. The main objective of this study was the assessment of the feasibility of applying a new approach i.e., Acoustic Emission (AE) technologies for monitoring cavity growth during the UCG process in order to determine the mechanism of AE generation and then visualize fracturing activities in the gasification zone. To this end, a series of ex-situ UCG models were constructed. During coal combustion, temperatures inside the coal, contents of the product gases (reported in literature [52]), and AE activity were successively monitored at controlled feed gas (air/oxygen and steam) flow rates. Based on this, crack distribution models were developed using AE moment tensor analysis. The obtained results can be used for the observation of fracture configuration and cracks in order to develop fundamental data to be used in technology and simulation methods for evaluating the combustion zone during UCG.

2. Material and methods

2.1. Description of the experimental setup

In this study, experimental simulation of UCG in coal block samples was conducted using ex-situ laboratory UCG models, which were used to analyze fractures occurring in the gasification zone by varying several operational parameters (linking-hole type, feed gas, operational time, etc.).

The coal samples for the UCG trials were obtained from the Kushiro and Bibai Coal Mine located in Hokkaido, Japan. This coal is bituminous and characterized by a high sulfur and relatively low moisture content [52]. The raw coal blocks were shaped into rectangular cross sections and cast in a drum can with concrete in order to simulate both the coal seam and the surrounding rock layers. The reactor walls were made of heat-resistant concrete of a specific thickness, thus providing an internal active space.

A schematic of the gasifier structure is shown in Fig. 1. This setup consists of the simulated gasifier, a gas agent supply system, a syngas cooling plant, and a gas chromatograph for analyzing the product gas compositions at specific sampling times. The location and propagation of the gasification zone were monitored by measuring the temperature using thermocouples and by monitoring fracture using AE sensors equipped within the models.

In a typical UCG process, two vertical wells are drilled into the coal seam. These are designed for injection and production, and they are connected by an underground gasification gallery created using various linking techniques at some distance apart. However, it is difficult to employ the universal design of an UCG system directly to a target underground coal seam because the geological structure and ground conditions are required to be considered. An underground reactor is created in a UCG system, which expands around the gasification channel. The underground link, i.e., the gasification channel between the two wells, needs to be established in the target coal seam because the underground primitive conditions, surrounding rock characteristics, and coal properties cannot readily provide a porous gasification channel for the gas flow and ensure the continuation of the gasification process. Moreover, the geometry and dimensions of the experimental model appear to affect the product gas and gasification efficiency. In this