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An experimental ex-situ study of the suitability of a high moisture ortho-lignite for underground coal gasification (UCG) process

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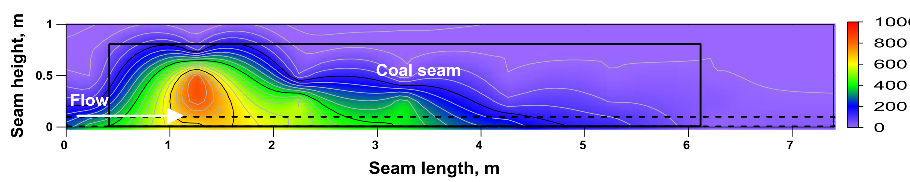
HIGHLIGHTS

- A multi-day experimental simulation of UCG using large bulk samples of ortho-lignite was conducted.
- The average moisture content of the coal was 46.5 wt%, and its calorific value was 12.6 MJ/kg.
- The overall process energy efficiency was estimated at 59%, and the average gas calorific value was approximately 7.2 MJ/N m^3.
- The study demonstrated that oxygen-blown UCG of high moisture lignites may be a feasible option.

GRAPHICAL ABSTRACT



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ABSTRACT

An experimental simulation of underground coal gasification (UCG) using large bulk samples of ortho-lignite was conducted in an ex-situ laboratory installation. The main goal of the experiment was to evaluate the suitability of the high-moisture lignite for UCG. The average moisture content of the coal feed was 46.5 wt%, and its calorific value was 12.6 MJ/kg. Changes in the gas composition, the gas production rates, and the distribution of temperatures in the artificial coal seam were measured over the course of the experiment. During the 120 h UCG trial, gas with an average calorific value of approximately 7.2 MJ/N m^3 was produced. The overall energy efficiency of the process was estimated at 59%. The study results demonstrated that exploitation of the high-moisture lignite deposits using oxygen-blown UCG may be a feasible option. Therefore, this technique may be considered as an attractive option for the extraction of low-rank Miocene ortho-lignites, large deposits of which are located in Poland and in many other countries around the world.

1. Introduction

A significant proportion of the world's coal reserves are composed of low-value coals, predominantly lignites and high-ash bituminous coals. Lignite, the recoverable reserves of which are estimated at 18% of the total global coal reserves, remains a crucial contributor to the energy supply in many countries [1]. Specific physicochemical properties of these low-rank coals impose many restrictions on their handling and utilisation. Lignites usually are characterised by high moisture contents, reaching up to 60 wt%, and consequently poor calorific values [2]. Lignites are also very susceptible to spontaneous ignition. Because these properties considerably increase the risk and cost of transportation, lignites must be used in close proximity to their mining sites.

Underground coal gasification (UCG) is a technique that converts coal underground (*in situ*) into a valuable gas product [3–7]. Because the main gas components are H_2, CO, CH_4, and CO_2, it may be used directly for electricity and heat production or as a feedstock for chemical synthesis (syngas) [8,9]. In its

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simplest configuration, UCG involves preparation of two vertical boreholes into the coal seam, one for the supply of oxidants (oxygen, air and steam), and another for the gas recovery (production well), achievement of hydraulic connectivity between them (horizontal drilling) and efficient seam ignition. The gas is produced as a result of a series of primary exothermic and endothermic reactions between coal and supplied oxidants and many secondary physicochemical phenomena, including gas-phase reactions and coal pyrolysis. The UCG process has recently attracted a considerable attention as an alternative to the traditional mining methods. UCG may provide a convenient source of energy from coal seams for which traditional coal extraction techniques are economically, technically or environmentally not feasible [10].

Although UCG has been studied internationally for a long time, there are still many technological difficulties to be solved. Regarding the UCG of low-rank coals, most of the global research activities were focused on hard lignite (meta-lignite). In contrast, Polish lignite resources are limited almost exclusively to soft lignite (ortho-lignite). The feasibility of UCG of high-moisture ortho-lignites is one of the issues to be scientifically explained [11].

There are 90 well documented lignite deposits in Poland, distributed into eight regions. Their total geological resources are estimated at approximately 36,132 million tonnes. The Miocene ortho-lignites, due to their abundance and geological conditions, are of dominant industrial importance. These ortho-lignites are characterised by high moisture content (>50%) and relatively low calorific value and are mined exclusively using the open-cast method. Because Polish lignite deposits are usually of shallow depth, many of them do not meet the site selection criteria for UCG [12]. Polish ortho-lignites are primarily used for the electricity production (approximately 65.0 million tonnes per year). Similar lignite utilisation patterns are also characteristic for other European lignite-producing countries, of which Slovenia, Bulgaria and Romania have recently shown the most intensive research activity in the development of UCG technology [13–15].

The issue of the suitability of high-moisture lignites for UCG is still questionable. The ex-situ simulations of UCG using large samples of Polish ortho-lignites (length of 2.5 m) revealed that the coal moisture content is one of the crucial parameters determining the gasification conditions, the quality and amounts of the products, as well as the suitability of lignite for UCG [11,16,17]. The average calorific value for the oxygen-blown laboratory UCG experiment with ortho-lignite (moisture content 53.0 wt%) was 5.2 MJ/N m^3 [16]. Gasification with an oxygen-enriched air (OEA) resulted in a considerable deterioration of the gas calorific value to 4.18 MJ/N m^3 for the optimum established oxygen/air ratio [11]. The high moisture content in the tested lignite resulted in a very poor thermal efficiency (20%) and low gas quality because a considerable amount of thermal energy was consumed for water evaporation.

This article presents the result of an experimental study on the suitability of one of the Polish ortho-lignites for the UCG. The main differences with respect to the previous experimental work [16,17] were considerably larger dimensions of the artificial coal seam. A multi-day oxygen-blown UCG experimental simulation was conducted in a laboratory ex-situ installation designed for tests with large bulk samples.

2. Materials and methods

2.1. Description of the experimental installation

Large-scale surface installation was used to experimentally simulate the underground coal gasification process in the laboratory conditions (Fig. 1). An essential part of the installation is a gasification chamber, where the underground geological conditions of the coal seam are reproduced. The maximum length of the artificial coal seam is approximately 7 m. Oxygen, air and steam can be used as gasification reagents, supplied individually or as a mixture. Nitrogen is used as a safety agent for inertising and cooling down the reactor after gasification. The experimental set-up was designed to conduct UCG tests under an atmospheric pressure regime.

The raw UCG-derived gas is subject to scrubbing with water to reduce its temperature, remove particulate matter and condense high boiling tar components. The subsequent gas treatment step involves separation of aerosols. The produced gas is finally burnt in a natural gas-fuelled thermal combustor. The concentrations of the main gaseous components are analysed using the gas chromatography (GC) technique. An Agilent 3000A Micro GC device is used for these purposes. The distributions of temperature fields during the experiments are recorded by thermocouples (Pt10Rh-Pt) installed directly in the various zones of the reaction chamber. The inlet and outlet gas temperatures (T) and pressures (p) are also monitored as the crucial operational parameters.

2.2. Lignite characteristics and preparation of the artificial coal seam

The bulk samples of lignite for the UCG trial were obtained from the Turów deposit located in south-western Poland. The deposit is currently extracted by the Turów Mine using the open-cast method. This deposit of ortho-lignite (Miocene age) is characterised by a high moisture content and by a relatively low calorific value (Table 1).

The raw lignite samples, each having dimensions of approximately 0.9 m × 0.9 m × 1.5 m after initial processing, were used to create a continuous artificial coal seam of the total length of 5.7 m, width of 0.8 m and thickness of 0.8 m.

The gasification channel was drilled along the bottom part of the seam (Fig. 2). The dimensions of the channel were 0.1 m × 0.1 m. Sand was used to fill the voids between the reactor's walls and the coal seam and for the preparation of the roof stratum.

27 thermocouples were installed inside the reactor to record the temperature profiles during gasification (Fig. 2). The Nos. 1–6, 9–13, 15–20 thermocouples were located inside the coal seam. The Nos. 22–28 thermocouples were located inside the overburden sand stratum, and the thermocouples denoted as 14 and 21 were installed in the sand layer, behind the coal seam.

2.3. Experimental procedure

The coal seam was ignited using a pyrotechnic charge, placed in the gasification channel at a distance of approximately 1 m from the face of the coal seam. The gasification process was started by adding oxygen (99.5% purity) into the ignited coal seam. An initial oxygen supply rate was 3 m^3/h and was gradually increased over the course of experiment, up to the maximum value of 6 m^3/h in the final phase of the gasification process. The oxygen flow rate modulations were necessary to sustain the optimal thermodynamic conditions for gasification reactions. Due to the over-stoichiometric water content in the raw coal, no water addition was required. The gasification process was conducted under near-ambient pressure conditions. Concentrations of the syngas components (H_2, CO, CO_2, CH_4, N_2, O_2, C_2H_6, and H_2S) were analysed in one hour time intervals. The laboratory simulation of the UCG lasted for 120 h.