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Energy and exergy analysis of alternating injection of oxygen and steam in the low emission underground gasification of deep thin coal

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HIGHLIGHTS

- We model UCG process with alternating injection of steam/oxygen.
- We used exergy analysis to investigate the practicality of the process.
- We show that the alternating injection UCG is practical at low pressure.
- Zero emission conversion of coal is not currently practical.
- Co-injection of steam/oxygen results in a higher recovery of coal.

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ABSTRACT

Recent studies have shown that by coupling the underground coal gasification (UCG) with the carbon capture and storage (CCS), the coal energy can be economically extracted with a low carbon footprint. To investigate the effect of UCG and CCS process parameters on the feasibility of the UCG-CCS process, we utilize a validated mathematical model, previously published by the same authors, that can predict the composition of the UCG product, temperature profile, and coal conversion rate for alternating injection of air and steam for unmineable deep thin coal layers. We use the results of the model to conduct an energy and exergy analysis of the UCG process. We study the effect of various process parameters on the efficiency of the UCG process, the zero-emission recovery factor of coal, and the total CO_2 emission of the process. Moreover, we compare the alternating injection of air/steam with the injection of an air and steam mixture.

Exergy analysis shows that the alternating injection of air/steam describes a practical process for UCG at low pressure. However, injecting a mixture of steam and oxygen results in a practical recovery factor of coal higher than the alternating injection process. Additionally, we show that the zero-emission conversion of unmineable deep thin coal resources in a coupled UCG-CCS process, that is not practical with the current state of technology, can be realized by increasing the energy efficiency of the carbon dioxide capture process.

1. Introduction

According to the International Energy Agency, more than 40% of the global electricity production is from coal power plants [1]. The high carbon content (per unit heating value) of coal compared to other hydrocarbons and its worldwide utilization for electricity production makes coal one of the main contributors to the rising carbon dioxide concentration in the atmosphere. The increased societal concerns regarding the role of carbon dioxide concentration in the global climate change demands a more effective and cleaner utilization of coal. According to Friedmann and coworkers who analyzed the published data of the commercial UCG pilots, a low carbon content fuel can be produced by combining UCG and carbon capture and storage (CCS), with a considerably lower cost compared to the ex-situ surface gasification. The existence of mature CO_2 capture technologies for decarbonizing the UCG product stream and the proximity of the potential CCS sites to the coal resources [2] are among the reasons that may potentially lead to an economic UCG-CCS process [3,4]. However, Friedmann et al. point out

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Nomenclature

C_{fuel}	CO_2 emission [kg/J]
$\Delta h^{vap}_{H_2O}$	heat of vaporization of water [J/mol]
e_{CH_4}	methane emission factor [kg/J]
Ex_{coal}	CCS exergy requirement [J/(m^2 s)]
Ex_{comp}	compression exergy [J/(m^2 s)]
Ex_{net}	net recovered exergy [J/(m^2 s)]
Ex_{O_2}	oxygen exergy [J/(m^2 s)]
Ex_p	exergy of the UCG product [J/(m^2 s)]
Ex_{pump}	pumping exergy [J/(m^2 s)]
Ex_{steam}	steam exergy [J/(m^2 s)]
M_{CO_2}	CO_2 molecular weight [0.044 kg/mol]
N^t_C	carbon flux in the product [mol/(m^2 s)]
R^{pr}	practical recovery factor [–]
R^{ze}	zero-emission recovery factor [–]

that the coupling of UCG-CCS is not addressed in the existing pilot projects nor in the modeling and simulation studies [3].

Here, we employ the concept of exergy to first investigate whether it is possible to feasibly extract the deep (1000–2000 m) thin (1–3 m) unmineable coal resources that are abundantly found in European countries like Belgium, the Netherlands, Poland, Bulgaria and Great Britain [5]. Secondly, we investigate the possibility of reducing the CO_2 emission by coupling the UCG process to CCS.

Recently, several researchers have investigated the clean utilization of coal in the underground coal gasification [6], focusing on the electrical power generation. Prabu and Jayanti [7] proposed a process for coupling UCG with a solid oxide fuel cell (SOFC), combined with CCS. They suggested that the UCG syngas product can be upgraded to a gaseous product with a high hydrogen content, that is fed to a SOFC unit for the electricity production. Their energy analysis showed that the overall efficiency of the UCG-SOFC system is 32% and the exhaust gas stream from the process contains 95% CO_2 that is ready for compression and sequestration. For the UCG reaction, they used the experimental data of the Hoe Creek field trial [8]; it is the first successful trial for the injection of oxygen/steam mixture as the gasification agent, although the coal seam is located at only 40 m depth and the gasification is conducted at a low pressure. Nakaten et al. [9] developed a comprehensive techno-economic model that is able to estimate the cost of electricity, energy consumption, and CO_2 emission for a coupled UCG-CCS process where the produced syngas is consumed in a combined cycle gas turbine (CCGT) for the electricity production. In the model, they assumed a fixed composition for the UCG syngas product, which is based on the previously reported values for the deep UCG trials. They used their model to study the electricity production from a deep unmineable hard coal deposit in Bulgaria [10], and concluded that the UCG-CCGT-CCS can be a low carbon alternative to the current coal fired electricity production in Bulgaria. By conducting a sensitivity analysis, they showed that the cost of electricity is dependent on the UCG product composition with a variation of up to 9.8% [11], signifying the importance of the accurate prediction of the UCG product composition.

Moreover, several researchers have investigated the energetic and exergetic efficiency of the UCG process. Blinderman and Anderson [12] studied the data of the εUCG process applied to a 10 m thick coal layer at 140 m depth in Chinchilla, Australia. They showed that the overall efficiency of the electricity production from the UCG-IGCC (Integrated Gasification Combined Cycle) can reach 43%, which is comparable to a natural gas combined cycle (NGCC). Blinderman et al. [13] used the concept of exergy to maximize the efficiency of the reverse combustion linking (RCL) process; in the RCL process, high pressure air is injected into a low permeable coal layer and the combustion starts at the production well, propagating backwards to the injection well creating a high permeable link between the injection and production wells. Although here we look into a similar backward gasification process, we consider a process where a link is already established between the injection and the production wells. Eftekhari et al. [14] conducted an exergy analysis of underground coal gasification with simultaneous adsorption of carbon dioxide on pulverized calcium oxide and wollastonite. In their analysis they showed that production of calcium oxide is too energy-intensive for the low emission UCG process to be feasible. Moreover, they use a thermodynamic equilibrium model for the gasification process, which is not accurate specially at lower gasification temperatures. Bicer and Dincer [15] studied a novel integrated system, in which the produced syngas from a UCG process is utilized in an IGCC power plant and solid oxide fuel cells is used for electricity generation, with some of the electricity consumed for hydrogen production and the exhaust steam from the IGCC used for the recovery of heavy oil. They used an equilibrium model for the UCG process and the idea is mostly developed for the region of Alberta, Canada.

In summary, we address two main problems that are associated with the existing thermodynamic analyses of the UCG process; first, the simplified chemical equilibrium models that are used for the prediction of the final UCG product are not accurate specially when the process is controlled by kinetics or mass transfer [16]. Secondly, the analyses are mostly conducted for the shallow thick coal seams, where the gasification reactions occur at low pressure. These coal resources, however, are not abundant in, e.g., Europe. The gasification of deep coal seams must be conducted at higher pressures (close to the hydro-static pressure to avoid the water intrusion when the coal resources are connected to aquifers). It is known that high pressures is detrimental to the quality (i.e., heating value) of the UCG product. However, the effect of pressure on the carbon content of the produced syngas and consequently its impact on the exergy balance of the UCG-CCS process is not yet studied.

We address these problems by using a mathematical model that is developed for the gasification of thin deep coal seams and is able to predict the composition of the gaseous product of a UCG process, where air (oxygen) and water (steam) are injected alternately. In this process, the air injection period serves to heat up the coal and the surrounding strata, and the steam injection period serves to produce high quality gas recuperating the heat from the surrounding strata [17–20]. Here, we use the results of the model to perform an energy and exergy analysis on the whole process. Our objective is to find the efficiency of the UCG process in recovering the coal resources. Moreover, we quantify the total CO_2 emission of the process per unit heating value of the final products. We investigate the effect of various parameters including the steam to oxygen ratio in the feed stream, the temperature and pressure of the feed stream, and the gasification pressure on the recovery factor of the process and the carbon content of the product and net CO_2 emission of the process.

The organization of the paper is as follows: Section 2 gives an overview of the process and the mathematical model. In Section 2.3 the idea of the exergetic efficiency and recovery factor for an energy conversion process is described. The flow diagram and the major energy-consuming units of the overall process are discussed in Section 2.4. Then, we present the results of the model in Section 3 which includes the effect of steam/O_2 ratio on the quality of the UCG product when a mixture of oxygen and steam is injected. In Section 3.2, we perform an exergy analysis on the overall process and calculate the practical and zero-emission recovery factors of coal. Finally, we end with conclusions.