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Forward and reverse combustion gasification of coal with production of high-quality syngas in a simulated pilot system for *in situ* gasification

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HIGHLIGHTS

- A new forward and reverse combustion process for *in-situ* gasification was proposed.
- Lignite and bituminous coal, were gasified, producing high-quality syngas.
- Controlling conditions for reverse combustion gasification were identified.
- Inject gas flow and velocity of gasification flame were linearly related.

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ABSTRACT

This research focused on the feasibility and stability of applying the forward and reverse combustion approach to the *in situ* gasification of lignite and bituminous coal with oxygen or oxygen–steam mixtures as gasification agents, especially reverse combustion gasification. A high-quality syngas (H_2 and CO) could be obtained using the reverse combustion gasification technique combined with forward combustion gasification in a pilot system for *in situ* gasification. The gasification time was extended more than 25% using the reverse combustion approach. The controlling conditions for reverse combustion gasification were obtained by comparing and analyzing experimental data. The results show the relationship between the inject gas flow within certain limits and velocity of the gasification flame was linear during reverse combustion. The underground conditions of the coal seam and strata were simulated in a pilot-scale underground gasifier during experiments. The combustion gasification of coal was carried out experimentally for over 5 days. The average effective content (H_2 and CO) of syngas was in the range of 60–70%, meeting the requirement of synthesis gas. The optimal ranges of gasifying lignite and bituminous coal were found to be 1.5–2.0 and 1.3–1.75, respectively. The product gas flow was proportional to oxygen blast. These are expected to provide useful guidance on practical underground coal gasification operations and to give experimental evidence in support of theory.

1. Introduction

At recent underground coal gasification (UCG) technique has attracted increasing attentions [1]. This technique exhibits many potential advantages of technology and economy [2]. It mentions here to increase utilization efficiency of coal and improve economic environment-friendly performance as compared to the currently applied technologies of conventional coal exploiting and using [1–4]. Especially, Prabu and Jayanti have used the UCG technology in the carbon-neutral power generation and solid oxide fuel cell system [5]. These represent a huge potential and bright prospect for application and development of UCG technology. Moreover, the hydrogen manufacturing from underground coal gasification is one of effective and feasible methods for hydrogen production [6–8]. UCG technology differs from conventional coal gasification in surface reactors, in that it is an invisible process, so experimental simulation of underground coal gasification is essential to research the process, phenomena, theory and technology of UCG. The researchers of different countries have obtained important achievements using their respective experimental simulated UCG units [9–11]. The Laboratory and pilot scale simulated experiments were performed by shaftles-type underground coal gasification technique which is one of the main directions of the UCG research.

Generally, forward and reverse combustion approaches are used in shaftless-type underground coal gasification (UCG)

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processes [12–14]. In practical operations, reverse combustion has been widely applied to link the injection and production wells in UCG, and forward combustion has usually been applied to gasify the coal seam, using appropriate gasification agents [15–17]. Different gasification techniques should be selected to gasify coal according to coal seam thickness [18]. In essence, the single-phase forward gasification technique is performed to gasify a thin coal seam *in-situ*. Multi-phase forward and backward gasification techniques are carried out on thick coal seams to improve the efficiency of underground coal gasification. The operation of reverse combustion gasification is similar to backward gasification, *viz*., the product borehole is converted to an injection borehole [8]. Gasification agents are fed into the product borehole and production gas exits from the injection borehole under modern UCG conditions. Reverse combustion gasification differs from backward gasification in the direction between the flame (gasification working face) propagation and main gas flow, as shown in Fig. 1 [19]. The flame propagates in the opposite direction to the gas flow within the channel in the reverse combustion gasification process, whereas in backward gasification, the direction of the gasification flame follows the gas flow towards the outlet of the production gas. Thus, backward gasification is consistent with forward combustion gasification.

During forward combustion gasification, when the flame gradually moves to the product borehole, a large cavity will be formed in the coal seam through coal combustion gasification and overburden roof spalling. This reduces coal gasification efficiency and decreases the quality of production gas, for the following reasons [8]: (1) the dry distillation zone becomes increasingly shorter in the late stages of forward gasification. (2) The reactivity of coal significantly decreases after coal seams undergo dry distillation during forward gasification. (3) The reaction rates of coal combustion and gasification fall because of a decreasing concentration of gasification agents absorbed on the coal surfaces of the cavity wall. To increase coal seam gasification and enhance syngas quality, the injection borehole and product borehole should be exchanged during practical operation. In this way, gasification of coal seams will continue by shifting the direction of the injection gas and new gasification conditions are again formed. If the gasification flame moves in the direction of the injection gas flow, residual coal seams around the former product borehole would not be gasified, which wastes coal resource. To maintain gasification in the residual dry distillation zone, reverse combustion gasification could be applied in UCG processes and the production of high-quality syngas could be sustained.

Reverse combustion is an unstable process, in which the flame front is regarded as a displacement front [20]. The broad combustion flame will propagate to form a tube-like cavity of partially combusted fuels through coal seams [12]. Therefore, the reverse combustion approach is more suitable to the linkage stage in the UCG process. Moreover, all theories, models, field tests and laboratory experiments on coal reverse combustion with air in the literature are based on well linkage techniques [21,22]. Researchers in the former USSR invented combustion linking techniques in 1941 [23]. Subsequently, reverse combustion linking was successfully used by many countries in UCG field trials, including the former USSR, the United States, Canada, Uzbekistan, Belgium, Australia, and South Africa. During operation of these trials, high pressures were used to enhance linkage efficiency [24]. Skafa and Kreinin et al. described the characteristics of reverse combustion and summarized the results of their tests [12,25]. Laboratory experiments on reverse combustion are very difficult to carry out, particularly with coal and some of the reasons for this are summarized by Britten, as follows [20]: (1) after coal undergoes pre-oxidation, its structural integrity will be altered, greatly affecting the combustion characteristics of the coal. (2) RC in a combustion tube is affected by factors such as the permeability or thermal conductivity of the coal and the diameter of the tube. It is required that the permeability or thermal conductivity of coal are relatively low, and the dimensions of the tube is adequately large. (3) If the blasting rate of the gas is quite high, convective losses to the gas phase will inhibit thermal conduction in cold coal. In this case, the RC will revert to forward combustion. However, a number of laboratory experiments on reverse combustion in small-diameter tubes have been performed using various combustible media by workers in different countries, and the results of these studies can help to qualitatively understand the development of RC [26,27]. None of the industrial-scale UCG plants worked, except for the Yuzhno-Abinsk UCG plant, because of the oil and natural gas used widely throughout the world in the late 1980s. Accordingly, field trial research and laboratory experiments did not continue to develop [18]. However, theoretical developments and reverse combustion models have been constantly studied. Most recently, Blinderman et al. presented detailed theories for forward and reverse combustion and discussed gasification flame propagation in the channel of an underground coal gasifier [16,19,22]. They used mathematical models to simulate forward and reverse combustion in a gasification channel. The models include transport phenomena, and chemical reactions governed by conservation of mass, energy and species. The theories explain the relevant combustion phenomena in UCG processes and consider the effects of primary factors of flame propagation, the supply gas rate and other parameters. Nevertheless, there is a lack of field tests and laboratory experiments to support the theories. At present, there are no literature reports in which reverse combustion has been applied to gasify coal seams with gasification agents other than air in UCG operations. In this paper, we focus on the feasibility and stability of applying the forward and reverse combustion approach to the *in situ* gasification of coal with the production of high-quality syngas, especially reverse combustion gasification. A large-scale pilot system was designed and established to simulate UCG conditions. To validate the reliability and repeatability of the forward and reverse combustion gasification experiments, laboratory experiments on lignite and bituminous coal gasification with a mixed oxygen–steam agent were carried out in the simulated pilot system for *in situ* gasification, according to the characteristics of forward and reverse

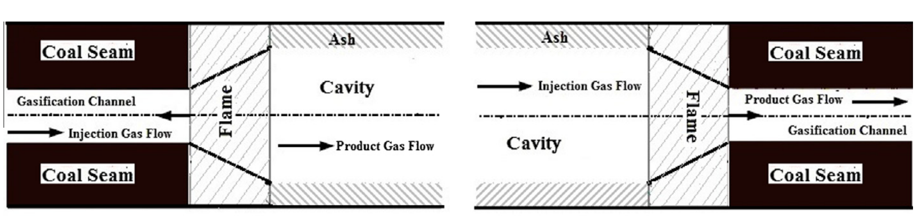

Fig. 1. Diagrams of reverse (a) and forward combustion gasification (b) [19].