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A process model for underground coal gasification – Part-III: Parametric studies and UCG process performance

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ABSTRACT

Underground gas gasification (UCG) is a clean coal technology which involves in-situ gasification of deep-seated underground coal. The process can be divided in two phases based on state of coal seam and direction of cavity growth. In phase-I, cavity grows mainly in vertical direction while in phase-II it grows in horizontal direction. The in-house simulator developed for both the phases of UCG has been reported earlier Samdani et al. (2016a,b). It incorporates reaction kinetics, flow patterns, spalling, heat and mass transfer effects. In this work, we take further insight and perform parametric studies to examine the effects of different operating conditions, coal properties and design parameters on key performance indicators i.e. exit gas quality, energy generation rates etc. The investigation revealed that the exit gas quality and rate of coal consumption are strong functions of spalling rates and kinetics of reactions; the coal having very low spalling tendency or less reactivity may not be favorable for the UCG process. An important parameter called *critical spalling rate* has emerged through this analysis. It is the property of given coal above which UCG is sustainable. In addition, model performance is also sensitive to inlet gas temperature, pressure and composition. Optimum performance of UCG is obtained at a steam to oxygen ratio of 2.5 and at the highest possible inlet gas temperature, operating pressure, and oxygen content in the feed. Among the design parameters, the length of outflow channel is very important as it strongly affects both the exit gas calorific value and its fluctuations with time. The predicted effects of different parameters are in accord with the observations during lab-scale UCG experiments and different field trials. This study demonstrates the importance of a process model to determine the best conditions for UCG process and to evaluate feasibility of the process for a coal seam under consideration.

1. Introduction

Underground coal gasification (UCG) can utilize coals at great depths that are un-minable by current technologies. These resources are comparable to the minable coal reserves [1] and therefore can lead to multifold increase in exploitable coal resources. There are several laboratory-scale, field-scale and few near-commercial scale UCG reactors operated in the past and several others are being studied and tested currently all over the world [2]. Like every other reactor, the performance of UCG reactor depends on the operating conditions, and it is not necessary for the optimum set of operating conditions to be similar for different coals as the process performance is strongly affected by properties of coal resources being targeted. There have been few studies and reports on the best operating conditions, best practices during UCG and guidelines for site selection criteria including the coal type and its properties. Bhutto et al. [3] presented a review of UCG fundamentals and applications wherein, different studies on the effects of variations in pressure, temperature, coal reactivity, thickness of coal layers, gasifying agent etc. are reviewed. Furthermore, a brief review of underground coal gasification presented by Shafirovich and Varma [4] provides comprehensive criteria for site selection including the coal rank and its properties. Burton et al. [5] in their report on best practices in underground coal gasification touched upon the optimum operating conditions and coal properties with an emphasis on environmental aspects and coal management. Eliot [6] also showed that the thickness of coal layer is an important parameter for UCG economics and process feasibility. He observed that there can be a multi-fold reduction in the heating value of the exit gas for thin coal seams. The huge reduction in the heating value is due to the excessive cooling resulting from heat losses to the surrounding rocks.

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Notations

Acronyms

UCG underground coal gasification
LLNL Lawrence Livermore National Laboratory
CFD computational fluid dynamics
RTD residence time distribution
CSTR completely stirred tank reactor
PFR plug flow reactor
CV calorific value

Perkins and Sahajwalla [7] demonstrated that the cavity growth rate is a strong function of operating parameters such as temperature, pressure and water influx, and the important coal properties including coal composition, critical conversion etc. However, to improve their model predictions further, a need for characterization of reactivity and thermo-mechanical behavior of different coals was realized. The choice of gasifying agent(s) is another important decision which has been shown to strongly affect the calorific value of exit gas [8]. Several studies have also been performed to understand the effects of changes in feed gas composition and a review can be found elsewhere [3]. An experimental study to investigate the effects of steam to oxygen ratio on gasification of Indian Lignite was undertaken by Daggupati et al. [9]. It showed that steam to oxygen ratio has an optimum value at around 2.5. In addition, they determined the best operating conditions using their laboratory-scale experiments. On the other hand, a set of early field trials in US have been extensively investigated by LLNL studies [5]. It provides a comparison of UCG performance for different coals, thereby showing the importance of coal properties. The study by Bhaskaran et al. [10] on the comparison of the performance of UCG for two Indian coals throws light on how coal properties, such as surface area and spalling tendency, influence the exit gas quality.

The available guidelines providing selection criteria for achieving better performance of UCG are either based on process know-how and experiences during different field trials or lab-scale experiments. However, the effects of variation in spalling behavior and kinetics of reaction of different coals, operating conditions and flow patterns inside UCG cavity have not been analyzed by using a comprehensive UCG process models. It leads to a need of an exhaustive model-based investigation of the effects of variation in coal properties and operating conditions on UCG process performance. This study is thus aimed at a thorough analysis by using the newly developed UCG process models [11,12] and identification of major factors responsible for the success of UCG. The operating parameters of interest include inlet temperature, operating pressure, feed gas flow rate and composition. The effect of coal properties, including coal spalling rate and reactivity, is also investigated. Other parameters such as flow distribution, length of outflow channel and heat losses to surrounding may also influence the exit gas quality.

2. Model description

The strategy used to model UCG process is unique in a way that it divides the process in two phases according to the state of the cavity and the observed distinct growth patterns [11]. The UCG process, described in Fig. 1, shows these two distinct phases of UCG. The main difference between Phase-I and phase-II is the direction of cavity growth in the respective phases. In phase-I, the cavity grows mainly in radial/vertical direction and the phase-II is characterized by dominant forward horizontal growth towards the production well. These two phases are separated from each other by the event of UCG cavity hitting the overburden. These are multi-zonal models and consider three distinct zones namely, a rubble zone on floor of the cavity, a cavity roof zone made of the coal seam and a void zone between these two, as shown in Fig. 1. In both, phase-I and II, the role of a phenomenon called spalling is very important. It is the thermomechanical failure of coal from roof of the cavity at high temperature. The spalling of coal from the roof exposes that coal to the reaction environment so that it can be easily consumed due to reactions with incoming gases and thereby it increases the rate of gasification. The spalling tendency of a coal depends on both inherent coal properties like internal heterogeneity, cracking behavior, moisture content and operating conditions like UCG temperature and gas environment [13].

For phase-I, the non-ideal flow patterns in the initial cavity are determined using computational fluid dynamics (CFD). The CFD results and RTD studies show that the complex UCG cavity can be approximately reduced to a computationally less expensive compartment model consisting of radial-PFR followed by a CSTR. The development of phase-I model is shown pictorially in Fig. 2. The illustrations show a schematic of UCG cavity, a tractable geometry mesh for CFD simulations, the velocity vectors showing flow patterns and the final compartment model based on these flow patterns and the RTD studies. The temperatures and compositions of both gas and solid are tracked in the rubble zone by solving for mass and energy balances of both phases and Darcy law for pressure drop in radial plug flow conditions. The void space facilitates mixing of volatiles from roof zone and product gases from the rubble zone, resulting in a change in gas composition depending on the extent of homogeneous gas phase reactions. The roof zone is included in the model to consider the flow of volatiles into the

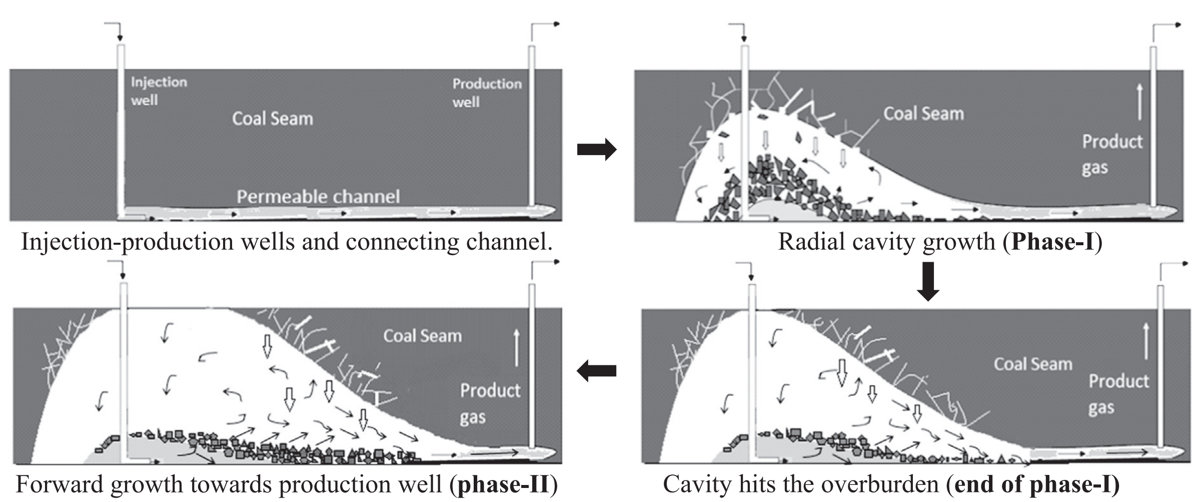

Fig. 1. Process of UCG, different steps involved and phases of UCG.