Fuel 123 (2014) 167–174

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Heat-affected zone analysis of high ash coals during ex situ experimental simulation of underground coal gasification

V. Prabu [a], S. Jayanti [b,*]

[a] Department of Chemical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India
[b] Department of Chemical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

HIGHLIGHTS

- Laboratory scale ex situ simulation of underground coal gasification (UCG).
- Identification and characterization of heat-affected zone during UCG.
- Comprehensive sampling of remnant coal surrounding cavity.
- Establishment of depth-wise profiles of volatile matter depletion.
- Testing with coals, lignite and wood.

ARTICLE INFO

Article history:
Received 25 September 2013
Received in revised form 7 November 2013
Accepted 8 January 2014
Available online 28 January 2014

Keywords:
Underground coal gasification (UCG)
Cavity formation
Heat affected zone
Ash layer resistance
Proximate analysis

ABSTRACT

Underground coal gasification (UCG) is a transient and evolving phenomenon in which many chemical and physical changes occur simultaneously and/or sequentially in various regions throughout the coal seam. Heat affected zones of dry and volatile depleted porous zones are formed up to a certain depth of the coal block leading to coal spalling. In the present work, we present a proximate analysis of the coal samples from various locations of the heat-affected zone (HAZ) during borehole combustion and gasification studies which simulate experimentally underground coal gasification. Results from HAZ studies of wood and four coals show that there is a considerable change in the volatiles to fixed carbon ratio in the depth direction and that the extent of variation depends on the coal as well as on the conditions prevailing during the experiment. These results have a potential bearing on the reactivity of the coal and the product gas composition.

1. Introduction

Underground coal gasification (UCG) is an important technology for the exploitation of the large fraction of the coal reserves that are too deep underground to be mined economically and offers possibilities of coupling with technologies for clean coal utilization and carbon capture and sequestration [1–3]. Development of the UCG technology is essential for countries like China and India which are large consumers of coal for power generation and which have large reserves of deep underground coal. For example, estimates reported by Ministry of Power in India in 2005 show that up to 13% of proven Indian coal reserves are at a depth of more than 600 m and a further 25% lie at a depth of between 300 and 600 m [4]. Indian coals are bituminous or sub-bituminous or lignite coals and typically contain a large amount of ash which cannot be easily washed. Large ash content in the coal leads to higher transportation cost of coal per MJ of energy, higher rate of erosion of power plant equipment as well as higher cost of fly ash disposal. Due to their high ash content, low calorific value and location at uneconomical depth, UCG is the most suitable technique to exploit these reserves. While UCG has been seen as a promising technology for a long time and has been used for commercial power production in the former USSR [5,6], there is limited experience at the level of large scale implementation. The cumulative amount of coal gasified in over forty years of operation in the USSR is about 15 million tones while in the US and Australia, it is only of the order of 50 and 35 kilo tonnes only [6]. This level of exploitation compares poorly with the current annual utilization of about 500 million tones of coal in India alone. Further, much of the field experience with UCG has been limited to rather shallow depths of 200 m or less. In order to develop UCG as a commercial technology making a significant contribution to the current energy needs, it is necessary to study a number of related issues such as the

* Corresponding author. Tel.: +91 44 2257 4168; fax: +91 44 2257 4152.
E-mail address: sjayanti@iitm.ac.in (S. Jayanti).

http://dx.doi.org/10.1016/j.fuel.2014.01.035

underground cavity formation, sustainability of product gas composition, choice of oxidant and gasifying medium, input flow rate of oxidant and gasifying medium, water influx and inherent moisture of the coal seam during gasification, tar condensation along the coal seam, effect of coal spalling with the growth of the cavity, the effect of ash layer resistance etc. A thorough understanding of the issues involved in these is necessary in making the technology commercially viable.

UCG has been studied for a number of decades starting with early work and commercialization in the former USSR wherein over 60 years of research on UCG between 1928 and 1996 including field tests and commercial projects resulted in the gasification of over 15 MT of coal [6]. A commercial UCG-fed power plant in Angren, Uzbekistan has been in operation for about 50 years. In the US, Lawrence Livermore National Laboratory (LLNL) conducted several experimental (both lab-scale and field trials) and theoretical studies on UCG in the 1970s and the 1980s [7–9] and about 30 UCG pilot plants were established between 1975 and 1988. These led to the development of technologies relevant to successful operation of UCG. However, with the availability of cheap oil, large finds of natural gas and more recently, shale gas, interest in UCG in the USA has dimmed considerably in the 1990s. Due to increased concerns about energy demand, supply and security, there has been renewed interest [10–21] in UCG in USA and several countries including China, Australia, Poland, South Africa and India. Several UCG field trials have been reported in China, Australia and New Zealand [10] although the experience has been rather limited. Australia began a large pilot plant in 2000 which produced syngas for three years before controlled shutdown. The possibility of using UCG for hydrogen generation is also highlighted in the recent results of Stancyzk et al. [19] who were able to produce syngas containing hydrogen in concentration of nearly 60% under certain conditions. Recent review articles on UCG [5,6,22] bring out the current status of UCG and the importance of research and developmental effort that is needed make it a viable technology.

UCG is a transient and complex phenomenon in which many chemical and physical changes occur simultaneously in various parts of the cavity; these include the removal of moisture, release of volatile matter, coal combustion, char gasification, tar condensation etc. The released volatile matter contains high hydrocarbons and high molecular weight species such as tar in the gaseous phase which may condense through the flow path as the product gas cools down. These reactions affect the coal seam to a certain depth and width and change its morphological structure. Heat affected zones of dry and volatile depleted porous zones are formed up to a certain depth of the coal block. Here, cracks are developed easily and the coal may crumble into small pieces and fall into the cavity in a process known as coal spalling. Coal spalling, if it occurs extensively, may play an important role in the cavity growth since it exposes more surface area for the heterogeneous reactions to occur and thereby increases the conversion rate. In our earlier work, the UCG cavity geometries have been simulated using laboratory-scale bore-hole combustion and gasification experiments on wood and coal [20,21]. While small scale set-ups do not bring out all the features of a real UCG plant, many of the physic-chemical processes are well captured in the small set-ups since similar materials, similar temperatures and similar gaseous environment can be created. The results associated with these effects can be extrapolated with some confidence to plant level operation. The flow rates, product composition and output, etc. will have to be arrived at through further quantitative modeling involving relevant conservation equations and constitutive models for the phenomena and processes occurring therein. The present work is a continuation of the laboratory-scale experimental studies and focuses on the analysis of the coal property variation in the heat affected zones. The morphological structure of the coal in this zone is studied by dissecting the coal block after the completion of UCG cavity simulation experiments and subjecting samples to proximate analysis. It is shown that there is a considerable change in the volatiles to fixed carbon ratio in the depth direction, which may potentially have a bearing on the reactivity of the coal and the product gas composition.

2. Experimental details

UCG studies have been conducted at IIT Madras using bore-hole experiments in blocks of coal or wood. Experiments have been carried out with four coals and wood from the tree *Acacia nilotica*. The proximate and ultimate analyses (from literature [20,21]) of these five fuel sources are given in Table 1. Coals #1 to #3 have nearly the same moisture content and volatile matter but differ significantly in the their ash content and fixed carbon. Coal-1 has highest ash content (24.6% by weight) of all the fuels investigated in the present study. Coal-2 has lesser ash and more fixed carbon than Coal-1. Coal-3 has only about 10% ash and nearly 48% fixed carbon. Coal-4, which is actually a lignite, has a very high moisture content (53%) and low ash (3%). The last fuel, wood, has comparatively the highest volatile content and the least amount of ash and will serve as a useful reference material for comparative studies. One can therefore expect to obtain significant differences in their response to the heat generated in the UCG cavity.

In order to observe the geometry of the cavity, each log/block was sliced lengthwise into two halves; the dimensions of these are given in Table 2. In each block, a gasification channel was created by milling rectangular slots of 0.75 cm depth along the axial direction at the centre in both the upper and the lower blocks which simulate the linkage between the injection and the production wells in UCG. The blocks were sealed with china clay at all joints to prevent gas leakage. The gasifying agent was supplied through a steel pipe inlet of 5 mm inner diameter to the bore hole at a constant volumetric flow rate. The location and propagation of the hot zone was monitored by measuring the temperature, using K type thermocouples, at four axial locations in the bore hole. Combustion was initiated in the bore hole at a distance of about 5 cm from the inlet by igniting a small lump of camphor. When the combustion front reached the end of the bore hole, the supply of the oxidant and gasifying agent were cut off which led to a quick stoppage of the combustion and the suppression of gasification. The blocks were then allowed to cool down in air for about an hour,

Table 1
Properties of the coal and wood block used in the present study.

S. No.	Fuel	Proximate analysis (as received basis) (%)				Ultimate analysis (dry ash free basis) (%)				
		MC	VM	Ash	FC	C	H	O	N	S
1	Coal-1	9.95	29.80	24.76	35.50	74.76	7.31	15.35	1.68	0.90
2	Coal-2	10.40	28.80	19.20	41.60	77.41	6.96	14.99	0.142	0.50
3	Coal-3	9.00	33.00	10.00	48.00	–	–	–	–	–
4	Coal-4	53.00	24.00	3.00	20.00	70.00	5.00	25.00	Trace	Trace
5	Wood	19.25	66.00	1.04	13.71	50.22	5.90	42.86	Trace	Trace