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Experimental studies on spalling characteristics of Indian lignite coal in context of underground coal gasification

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ABSTRACT

Underground Coal Gasification (UCG) is considered to be a clean coal technology primarily intended to utilize deep underground (>300 m) coal deposits. In this process, a mixture of reactant gases like air/oxygen and steam are injected directly to an ignited portion of underground coal seam. UCG involves complex interactions of different processes like drying, pyrolysis, chemical reactions and spalling. Spalling is detachment of small coal particles from the coal seam due to interconnection of cracks developed in it. It plays an important role by offering higher surface area to give improved performance. The mechanism of spalling and its characterization are not well understood. Furthermore, there are no well established experimental techniques to measure the spalling rates. This paper studies spalling behavior of a lignite coal, which is characterized by high moisture and volatile matter, and suggests a possible underlying mechanism. The rate of spalling was measured using an experimental setup under the UCG-like conditions. In this setup, a reacting coal block was attached to a load cell and suspended in a UCG-like environment. When the experiments were repeated under similar conditions with different blocks of same coal, it was found that there were variations in the rates of spalling. This might be due to the heterogeneity in coal blocks in the form of originally present fissures or weak regions. A UCG process model was used to explain these experimental results and also to investigate the effect of spalling rate on product gas calorific value. We believe that spalling happens due to formation and extension of cracks. Hence a microscopic crack pattern on a heated coal monolith was examined in different stages of heating to understand the mechanism of spalling. It is concluded that cracks are first formed during the initial stage of drying due to the capillary stresses developed due to removal of moisture from the pores and were further extended due to shrinkage of coal during pyrolysis. The detachment of coal particles happens due to horizontal linking of vertical cracks, which might result out of either horizontal cracks, if any, or available fissures and weak regions or relatively weak interlayer bonding at the bedding planes.

1. Introduction

The importance of coal as a fuel for economic growth is going to continue due to its abundance and technological developments in its downstream processing. Hence, it is necessary to utilize untouched coal deposits, most of which are available deep underground. Underground coal gasification is such a technology that provides access to coal deposits which are available at a depth of more than 300 m. It is also considered as a clean coal technology worldwide due to its lesser polluting and highly efficient nature. UCG, like surface gasification, extends the applicability of coal to transportation sector and chemical synthesis when it is combined with technologies like gas-to-liquid and hydrogen generation from syn gas.

UCG is a process of converting coal *insitu* into combustible product gas by injecting a mixture of reactant gases like air/oxygen and/or steam directly into an ignited portion of underground coal seam. The reactor in UCG process is a high temperature cavity formed by the consumption of coal during the ignition process and it grows three dimensionally into the coal seam during the process. The coal present at the roof of the cavity undergoes

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Nomenclature

A	area (m^2)
C_g	gas concentration ($kmol/m^3$)
C_p	specific heat (kJ/kmol/K or kJ/kg/K)
D_{eff}	effective diffusivity (m^2/s)
ΔH	heat of reaction (kJ/kmol)
H	enthalpy (kJ/kmol)
M	molecular weight (kg/kmol)
V	volume (m^3)
R	rate of reaction ($kmol/m^3/s$)
T	temperature (K)
a_{ij}	stoichiometric coeff of *i*th gas species in *j*th reaction
$a_{s,ij}$	stoichiometric coeff of *i*th solid species in *j*th reaction
h_T	heat transfer coefficient in rubble zone ($kW/m^3/K$)
h_{Tcav}	heat transfer coefficient between void and roof surface ($kW/m^2/K$)
k_{eff}	effective conductivity (kW/m/K)
$k_{y,cav}$	mass transfer coefficient between void and roof surface (m/s)
t	time (s)
v	velocity (m/s)
ε_r	radiation emissivity
ρ	solid density (kg/m^3)
σ	Stefan boltzman constant ($kW/m^2/K^4$)
τ	residence time (s)
ϕ	porosity
ν	gas flow rate (m^3/s)

Subscripts

0	initial value
c	cross-section
cav	void zone
df	drying front
dry	dry zone
g	gas phase
i	species index
in	inlet of a zone
j	reaction index
l	liquid phase
s	solid phase
$roof$	cavity roof
$spall$	spalled particles in the rubble zone
T	total
vap	vaporization
$void$	void zone
w	water
wet	wet zone

different processes like drying, pyrolysis, gasification and combustion. These processes result in crack formation and further, its extension in the roof of the cavity may lead to mechanical disintegrity. This failure of the mechanical structure of coal present at the roof of the cavity may occur at different scales. They are a. subsidence or total collapse of roof due to falling of large chunks of coal (particle size greater than 10 cm) and b. falling of small pieces of coal or spalling. Fig. 1 shows a simplified schematic diagram of UCG depicting the spalling process. In this work, we present a laboratory experimental technique to approximately measure the spalling rate under the UCG-like conditions, and throw a light on the possible mechanism and its role in UCG. Indian lignites are chosen for this work as they are potentially important reserves for UCG [1] and available in large quantities on the north western coastal belt of India.

Spalling is one of the cavity growth mechanisms during the process of underground coal gasification. The evidence of spalling comes from the post combustion excavation studies of UCG field trials as reported by Cena et al. [2] and also from observations made in small scale laboratory experiments as reported by Daggupati et al. [3]. During the early stages of UCG process, cavity growth mainly occurs due to the consumption of coal by chemical reaction [4]. Once the cavity gains a considerably large size, the cavity growth occurs due to spalling, mainly in vertical direction [5]. It is therefore necessary to incorporate the spalling behavior in the UCG process model that helps to predict the shape and size of a growing cavity and the product gas compositions at any given time. Even though different investigators [5–7] have used many ways to include spalling phenomenon in their process model, a more scientifically acceptable representation of spalling in UCG process model is not found due to its complexity and availability of limited experimental data [6].

Britten [5] considered spalling by using two failure parameters; a failure temperature T_f and a spalling length l_f, in their process model. Spalling is simulated by redefining the coal cavity interface when the temperature at a length l_f into the coal block exceeds T_f. This model assumes spalling to be a result of only a thermo-mechanical failure, and crack formation due to reaction is not considered to be the possible cause. Furthermore, experimental validation for l_f and T_f is not found in literature. Mortazavi et al. [7] proposed two hypothetical spalling mechanisms during the removal of moisture from a coal block i.e. strength loss model and tensile cracking model. In the strength loss model, spalling occurs due to extension of horizontal and vertical micro-cracks, which are formed due to the strength reduction of coal block caused by the destruction of equilibrium pore pressure on removal of moisture from the pores. The cracks can also be formed due to the extension of fissures already present in the coal block. The weakening of coal block is more predominant at the bedding planes causing horizontal cracks needed for detachment of coal pieces from the roof. In tensile cracking model, the vertical macro-cracks are formed by the shrinkage of coal on removal of moisture. The horizontal cracks, responsible for spalling, are either provided by gravity at the weakest portions such as bedding planes or the extension of already present fissures. It may be noted that their studies are restricted to only drying of coal and furthermore an experimental validation of the proposed spalling models is not available. In the present work, we use similar theoretical support to explain our results, in the context of UCG wherein, the coal block is subjected to pyrolysis and other chemical reactions, in addition to drying. In both the models, formation and extension of cracks play a vital role in the phenomenon of spalling. Su et al. [8] used acoustic emission and X-ray computed tomographic techniques to monitor and analyze the micro crack structure inside a heated coal specimen.

Upadhye et al. [9] studied spalling experimentally by suspending a coal block in hot stream of nitrogen and monitoring the weight of the coal block. But they could not observe significant amount of spalling using their apparatus for the types of coal they have studied. According to Hettema et al. [10], spalling of sedimentary rocks happens due to the steam pressure at the pores on drying. However, for spalling to happen by this mechanism, the permeability of the rock has to be very low and hence this mechanism may not be applicable to coal as it acquires highly porous structure during the course of drying and pyrolysis of coal.