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Research article

The role of ash layer in syngas combustion in underground coal gasification

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ABSTRACT

Underground coal gasification (UCG) proceeds generally in the presence of an ash layer on the coal (or char) surface. The ash layer would not only increase the mass transfer resistance to gases as reported in the literature but also lead to reactions of O_2 with syngas (CO and H_2) generated from the ash–char interface. This paper studies the effects of ash layer in a specially designed one-dimension gasification assembly using a bituminous coal char by analyzing the ash and the gases components. The ash content of the char is 26.3 wt.% and the deformation temperature (DT) is 1460 °C. It is found that at 1300 °C the ash layer does not reduce the O_2 mass transfer until it is thicker than 1.3 mm. The ash layer, however, allows O_2 to react with CO generated from the ash–char interface to form CO_2, which raises the local temperature in the ash layer leading to local ash melting and transfers the char reaction from partial oxidation by O_2 in the absence of an ash layer to the Boudouard reaction, i.e. between char and CO_2.

1. Introduction

Coal gasification is a major process in converting coal to clean fuels and chemicals. Although many coal gasification technologies, such as moving-bed, fluidized-bed and entrained flow bed, have been developed and practiced successfully worldwide, underground coal gasification (UCG) has been viewed as a potential technology that is low in cost and human labor [1]. The reactions in coal gasification are complex, including the initial pyrolysis of coal to yield volatile and nonvolatile (char) products followed by reactions of these products with gasification reagents, such as O_2, H_2O and CO_2, to produce syngas (CO and H_2). The limiting step of the overall process is the reaction of char with the gasification reagents [2].

Coal contains inorganic matters, commonly termed as ash. The ash contents of coals vary, from around 5 wt.% to as high as 50 wt.% [3]. An ash layer would always form on the char surface during gasification due to progressive conversion of solid carbon to syngas starting from the char surface. This layer of ash has been found to have a significant effect on mass transfer resistance of the gasification reagents as well as the syngas produced, and therefore reduces the gasification rate of the remaining char. This ash layer's effect is more severe in UCG, because the coal and ash move little during the gasification. As a result the overall gasification rate in UCG is controlled by the thickness of ash layer as indicated by Kyun [4]. It was reported that the coal and ash surface spalls during UCG, which exposes new coal surface to the gasification reagents, but this behavior does not always occur [5,6], and the newly exposed surface is covered quickly by the ash remained from gasification.

Ollero studied gasification of a char in CO_2 in a thermal balance and showed that the increase in mass transfer resistance caused by ash layer can be expressed quantitatively by an effectiveness factor [7]. The mass transfer resistance increases not only with an increase in the ash layer's thickness but also with an increase in gasification temperature when the temperature is higher than the melting point of the ash. Liu et al. [8,9] studied gasification of seven coals in CO_2 and showed that the increase in gasification rate with an increase in temperature is less for a coal with a lower ash melting point while higher for a coal with a higher ash melting point. A coal showed a lower gasification rate at temperatures higher than its ash's melting point due to increased mass transfer resistance of gas in molten ash that covered the char's surface.

It is worth to note that, in principle an ash layer not only increases the mass transfer resistance of the gasification reagents and syngas produced, but also provides a space for reactions of these gases, including combustion of syngas. This is shown schematically in Fig. 1, where CO generated from the surface of char reacts with O_2 diffused from the bulk gas to form CO_2 and generates heat. The heat may increase the ash temperature and alter the ash structure, leading to melting of the ash under certain circumstances. The CO_2 formed from the CO oxidation may diffuse in both directions and a portion of them would react with the char to yield CO. This behavior, however, has not been studied clearly in the literature.

The combustion of syngas in ash layer during UCG may be evidenced by behaviors observed in coal combustion experiments. It was shown that at temperatures higher than 1000 K the carbon–oxygen reaction yields mainly CO, which is then further oxidized to CO_2 in the gas phase

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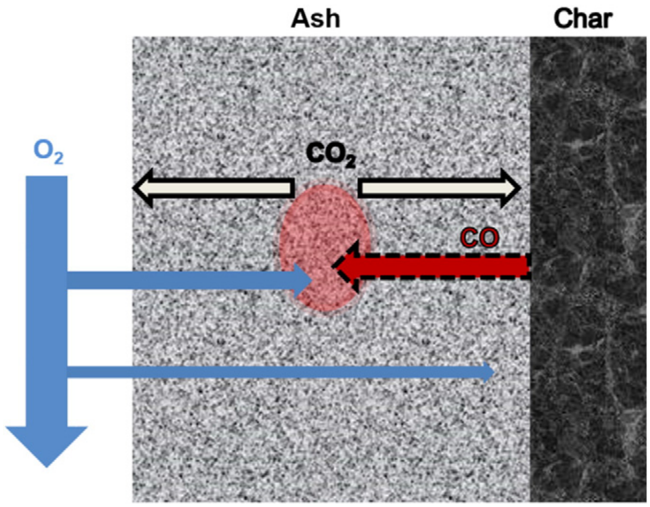

Fig. 1. Sketch of mass transfer and reaction of gases in ash layer on the char surface.

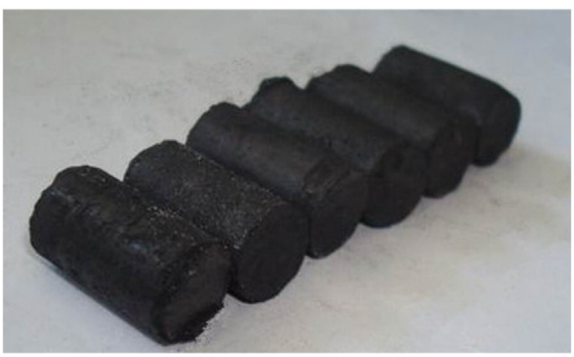

Fig. 2. Cylindrical char samples of Luxian coal.

[10]. Ross and Davidson [11] found that during combustion of coals of larger than 1 mm in size CO reacts with O_2 near the char surface, leading to a carbon particle temperature of up to 150 °C above bed temperature. The occurrence of syngas combustion in an ash layer can also be evidenced by the work of Kojima et al. [12,13], which showed that the temperature inside the char particles were about 20–400 °C higher than that of the gas phase during combustion.

As suggested earlier that the combustion of syngas in the ash layer may become more significant in UCG because the coal does not move and the geometric surface of coal is small in comparison to the amount of O_2 injected. Szekely and Dingsmoor reported that in UCG the combustion of syngas occurs mainly at locations close to the inlet of gasification reagents [14,15]. Furthermore, since the gasification reagents tend to flow towards the axial direction of the gasification tunnel [16], the direction of the pressure drop, instead of the radial direction towards the coal surface, it is more difficult for O_2 to access the coal surface, which leads to more combustion of syngas in the gas phase [17]. The UCG field trials in United States and India also indicated over-combustion of syngas that resulted high CO_2 content in syngas [18]. The efforts of Yu et al. in solving the problem by extending the length of UCG tunnel still resulted in high CO_2 content in syngas [19].

It is clear that, based on the discussion presented above, the occurrence of syngas combustion in ash layer over the char surface is very possible in UCG and the heat generated from the combustion may result in a high temperature zone which promotes melting of ash and reduces the mass transfer rate of gases. It is therefore interesting to verify the phenomenon experimentally. This work studies the changes in ash structure during one-dimension gasification of cylindrical char samples at various temperatures to seek clues of ash melting by syngas combustion.

Table 1
Proximate and ultimate analyses of Luxian coal and char.

	Proximate analysis (wt.%, ad)			Ultimate analysis (wt.%, daf)				
	M	*A*	*V*	C	H	O*	N	S
Coal	1.51	21.29	17.60	86.84	4.25	7.28	1.28	0.35
Char	0.63	26.32	4.74	90.37	1.41	6.50	1.31	0.41

Note: *M*: moisture; *A*: ash; *V*: volatile matter content; ad: air dry; daf: dry-and-ash-free basis; *: by difference.

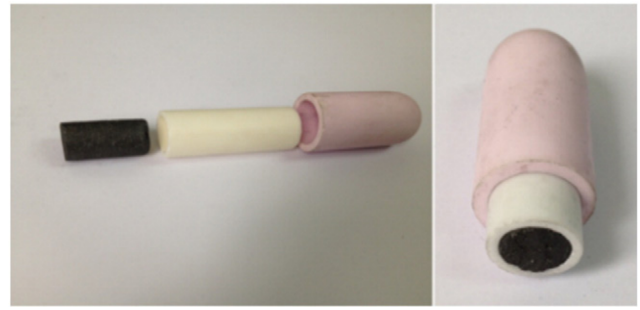

Fig. 3. Sample assembly.

2. Materials and methods

2.1. Sample preparation

A Chinese low volatile bituminous coal, Luxian coal, is used in the study. Cylindrical coal samples were made from large pieces of the

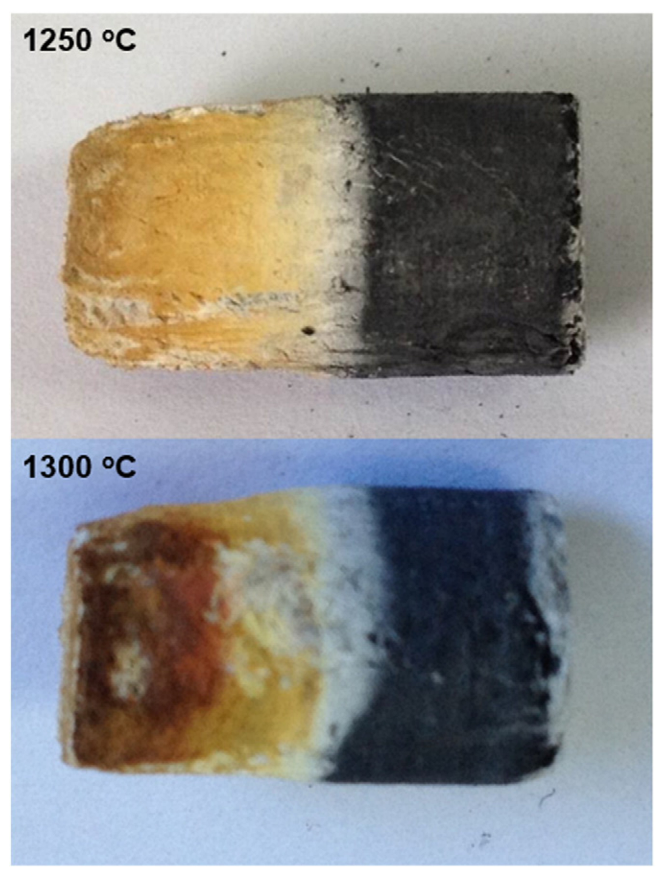

Fig. 4. Samples subjected to gasification for 40 h.