

Effect of Biomass Char Additives on the Hydrogasification Behavior of a Bituminous Coal

Huaili Zhu,^a Xingjun Wang,^{a,b,*} Xueli Chen,^{a,b} and Guangsuo Yu,^{a,b,*}

The hydrogasification behavior of a Chinese bituminous coal with three different biomass char additives, *i.e.*, sargassum char (SG char), saw dust char (SD char), and wheat straw char (WS char), was studied in a pressurized fixed bed reactor. The effects of the biomass char amount (0 to 30%), pressure (0.1 to 4 MPa), and temperature (973 K to 1073 K) on hydrogasification reactivity of coal were investigated. The results showed that the SD char and WS char improved the hydrogasification reactivity of coal noticeably, but for the SG char, the improvement at 973 K was not obvious because of the high content of chlorine. For all samples, the hydrogasification reactivity increased with increasing temperature and pressure. Moreover, experiments involving coal with different ash of biomass chars were conducted to verify the catalytic effects of alkali and alkaline earth metal (AAEM) species in the biomass char.

Keywords: Hydrogasification; Bituminous coal; Biomass char; Fixed bed reactor

Contact information: a: Key Laboratory of Coal Gasification and Energy Chemical Engineering of Ministry of Education, East China University of Science and Technology, 130 Meilong Road, Xuhui District, Shanghai, 200237 (PR China); b: Shanghai Engineering Research Center of Coal Gasification Shanghai, 200237 (PR China); *Corresponding authors: wxj@ecust.edu.cn; gsyu@ecust.edu.cn

INTRODUCTION

Coal has been the main fossil fuel for a long time and will continue to be an important component in China's energy consumption. However, coal combustion has caused many environmental problems. Gasification technology is the main conversion technique used to produce syngas, which is widely used in industry (Minchener 2005; Castaldi and Doohar 2007). The hydrogasification of coal has been a research hotspot because of the increasing demand for natural gas in China and because it has the potential to produce substituted natural gas from coal (Lee *et al.* 2006; Ding *et al.* 2013). Compared with other technologies, hydrogasification has many advantages (Yan *et al.* 2015); for example, the carbon methanation reaction is strongly exothermic, so no additional heat is required to maintain the gasification temperature except the initial stage of coal pyrolysis. The direct product of hydrogasification is methane, so no additional methanator is required. The efficiency of hydrogasification is usually higher than other gasification technologies and can reach 80%, and the hydrogasification reactivity can be easily enhanced by increasing the pressure.

Coal hydrogasification occurs in two main stages: coal pyrolysis with the release of volatiles, and char hydrogasification. The reaction rate of char hydrogasification is much slower than that of coal pyrolysis. Thus, char hydrogasification is the reaction rate-limiting step during the hydrogasification process (Tomeczek and Gil 2010). To improve the hydrogasification reactivity of coal, researchers have performed several research studies. Hong *et al.* (2013) used potassium- and sodium-based catalysts and found a significant effect on the formation of methane under a hydrogen atmosphere. Murakami *et al.* (2000)

studied Ni catalytic hydrogasification of coal and found that nickel species had a good catalytic effect on the hydrogasification reactivity of brown coal. Eutectic salts were also shown to be good catalysts for the hydrogasification of coal (Sheth *et al.* 2004). In addition to adding a catalyst, other methods have also been used. Rizkiana *et al.* (2014) used biomass ash to promote the reactivity of low rank coal and found that it was a promising method for the co-utilization of coal and biomass. Other researchers used biomass directly *via* co-gasification of coal and biomass because of the synergy between coal and biomass.

Biomass, as a renewable energy source, is considered an environmentally friendly fuel and contains less sulfur. As a developing country, China generates a large amount of biomass residue each year, such as agriculture residue, forest residue, and seaweed residue. Unfortunately, most of the biomass is abandoned or combusted directly because of its low energy density and high transportation costs. So, it is worthy to study biomass utilization. The most efficient way of biomass utilization is co-utilization of coal and biomass including co-pyrolysis (Li *et al.* 2013, 2014; Quan *et al.* 2014) and co-gasification (Jeong *et al.* 2014; Masnadi *et al.* 2015; Pu *et al.* 2015). It is found that the pyrolysis and gasification process have synergistic effects, which is mainly caused by the catalytic effect of alkali and alkaline earth metal (AAEM) species in the biomass (Brown *et al.* 2000; Krerkkaiwan *et al.* 2013).

Most of the cited studies deal with the application of biomass to the coal gasification, but biomass for hydrogasification is not well studied. In this paper, three types of biomass chars, *i.e.*, sargassum char (SG char), saw dust char (SD char), and wheat straw char (WS char), were used as additives for different AAEM species contents in hydrogasification experiments of a Chinese bituminous coal. The biomass was first pyrolyzed into biomass char, and the char samples were then mixed with coal at set mass ratios. The mixed samples were gasified in a pressurized fixed bed reactor using hydrogen as the gasifying agent. The effects of the biomass char type and the ratio on the hydrogasification behaviors were investigated as well as the effects of the gasification temperature and pressure. In addition, the synergetic and inhibiting effects were revealed, helping to understanding the interactions in the experiments.

EXPERIMENTAL

Raw Materials

A Chinese bituminous coal (Shenfu coal denoted as SF) and three types of biomass, *i.e.*, wheat straw, sawdust, and sargassum, were used in this study. Shenfu coal, collected from Shanxi province of China, is a typical bituminous coal with low ash content. Before the experiments, the raw coal was dried at 378 K for 24 h and was then pulverized and sieved to obtain a fraction sample of particle sizes from 75 to 125 μm . Wheat straw, collected from Jiangsu province, is the most abundant agriculture residue in China and is rich in alkali metals. Sawdust was collected from a furniture factory in Shanghai, and sargassum was collected from the eastern coast of China. The biomass was pulverized and sieved to obtain a fraction sample of particle sizes from 180 to 400 μm .

Biomass Char Preparation

Char samples were prepared in a fixed bed reactor. Before the pyrolysis experiments, the biomass was dried at 378 K for 12 h. In each run, 20 g of biomass was placed in the middle area of the reactor. The reactor was heated at a rate of 20 K/min to the

pre-set temperature under a flow rate of 1 L/min N₂ gas. The flow rate of N₂ was controlled by mass flow meters. The temperature of the isothermal zone reached 1073 K, at which point it was stabilized for 60 min until most of the volatiles had evaporated. Then, the reactor was cooled to room temperature under an N₂ atmosphere. The residual chars were ground to particles with diameters of less than 180 μm. Intraparticle diffusion could be ignored, as the particle size of the char was smaller than 180 μm (Radović *et al.* 1983). All samples were kept in a desiccator until they were used in the hydrogasification experiments. The obtained biomass chars are denoted WS char, SD char, and SG char. The characteristic analysis of the raw materials and biomass char samples is summarized in Tables 1 and 2.

Table 1. The Proximate and Ultimate Analyses of Samples

Sample	Proximate Analysis/db (%)			Ultimate Analysis/daf (%)				
	V	FC	Ash	C	H	N	S	O*
SG	35.58	5.81	55.81	44.94	5.97	1.92	3.73	43.44
SD	79.66	12.70	5.20	44.16	6.59	0.56	0.34	48.35
WS	72.07	15.29	10.02	43.07	6.57	0.92	5.92	43.52
SF	33.29	58.65	8.06	74.20	4.21	0.97	0.63	11.93
SG char	2.79	6.49	89.84	90.01	0.39	0.41	3.32	5.87
SD char	7.35	70.4	20.57	84.37	1.43	0.32	0.31	13.57
WS char	8.31	61.89	25.65	79.27	1.55	0.39	1.44	17.35

[db]: dry basis; [daf]: dry ash-free basis; [*]: calculated by difference

Table 2. Ash Composition of Materials

Constituent %	SiO ₂	Al ₂ O ₃	CaO	MgO	Fe ₂ O ₃	K ₂ O	Na ₂ O	Cl
SF	44.52	17.21	13.85	1.55	11.78	1.35	1.89	-
SD char	42.48	12.71	24.13	4.48	6.29	2.90	1.46	-
WS char	60.86	2.55	8.39	3.80	1.02	9.04	6.18	0.59
SG char	12.35	2.87	10.97	3.66	1.34	17.39	18.11	29.24

Hydrogasification Apparatus and Procedure

The hydrogasification behavior of the samples was investigated using a pressurized fixed bed reactor, as shown in Fig. 1a. The system is primarily composed of four parts: gas feeding, reactor, controlling units, and analysis units. The reactor (0.5 m i.d. and 1.0 m height) is made of a special heat-resistant Inconel 625 alloy, designed to maintain up to 1223 K and 6 MPa. Figure 1b shows a detailed diagrammatic sketch of the fixed bed reactor. Metal supports and quartz sand were first added to the reactor, followed by an alundum tube (50-cm height), and 5-g samples in each run were placed in the middle area of the reactor. With the use of quartz and the alundum tube, the samples were not in direct contact with the metal tube, avoiding the catalytic effect of the metal tube on the gasification of the coal.

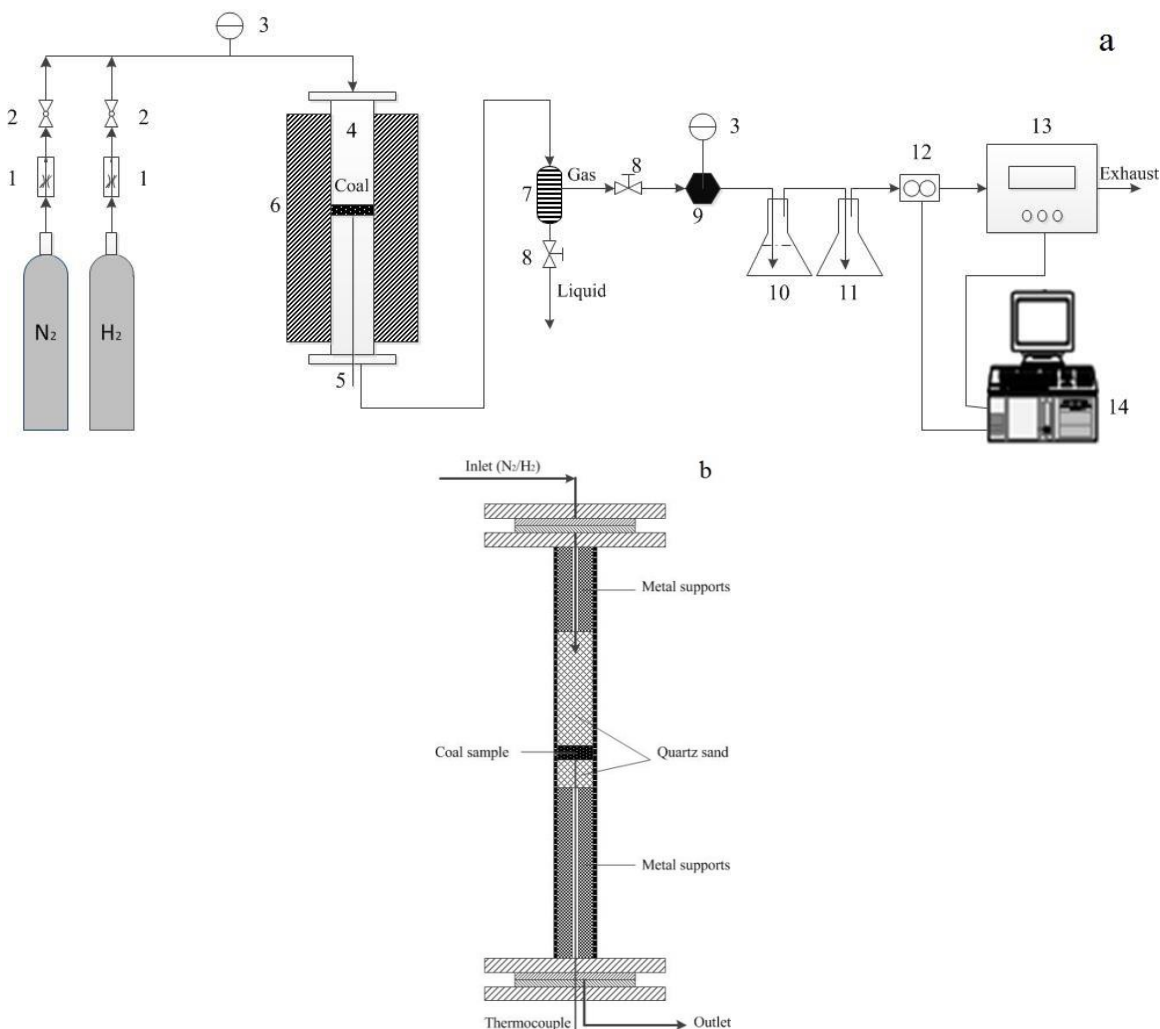


Fig. 1. Schematic diagram of the fixed-bed reactor system. 1: mass flow controller; 2: check valve; 3: pressure gauge; 4: fixed-bed reactor; 5: thermocouple; 6: electric furnace; 7: liquid/gas separator; 8: valve; 9: pressure regulator; 10: gas washing bottle; 11: gas drying bottle; 12: flow meter; 13: online gas analyzer; 14: computer

Before each experiment, the reactor was pressurized with nitrogen gas (99.999%) until it reached the predetermined pressure. To ensure safety, the seal of the system under high pressure was tested. If the seal met the system requirements, there was no gas leaking, and the outlet gas flow rate was nearly the same as the inlet gas flow rate, with a stable pressure. The nitrogen gas was replaced by hydrogen gas at a flow rate of 1 L/min, and the experiment was conducted.

In each run, the sample was kept at a total amount of 5 g. The ratios of biomass char were 10%, 20%, and 30% (wt.), which meant that the masses of biomass chars were 0.5, 1, and 1.5 g, respectively. The method of biomass char loading was physical blending. The furnace was heated at a rate of 20 K/min until it reached the predetermined temperature. Meanwhile, the flow rate of the outlet gas was measured by a flow meter, and the major gaseous products, such as methane, carbon monoxide, and carbon dioxide, were quantitatively determined using an online non-dispersive infrared flue gas analyzer (Gasboard-3100, Wuhan Cubic Optoelectronics Co., Ltd., Hubei province, China). At the end of each experiment, pure N₂ was purged into the reactor until the reactor was cooled

to room temperature. The residues were collected for further analysis. For calculating the theoretical gas volume, experiments of coal gasification and biomass char gasification were carried out, respectively.

Analysis

The proximate and ultimate analyses of the raw materials and chars were conducted according to the Chinese standards GB/T 212-2001 (2001) and GB/T 476-2001 (2001), respectively. The ash constituents of the char samples were determined using an X-ray fluorescence spectrometer (XRF, AdvantX, Association of Research Libraries, Switzerland), and the ash was obtained at 1088 K.

The experimental gas yield was compared with the calculated data. The online, non-dispersive infrared flue gas analyzer (Gasboard-3100) recorded the instantaneous flow rate of all gas products and the percentage of each gas every second. The experimental gas yields were calculated based on this data.

Flame atomic absorption spectrometry (FAAS) was adopted to determine the content of K and Na in SF-SGC and hydrogasification residues. The materials were washed with about 50ml ultrapure water and filtered. The solutions were transferred to 100 mL propene polymer volumetric flasks and made up to volume with ultrapure water. The FAAS was used to determine the K and Na content and the standard deviation is less than 3%.

The calculated production gas volume (V_{cal}) is the co-gasification result, assuming that there are no interactions between the coal and biomass char during the hydrogasification process. V_{cal} is calculated as follows,

$$V_{cal} = V_{bio} \times x + V_{coal} \times (1 - x) \quad (1)$$

where V_{cal} is the calculated gas volume, V_{bio} and V_{coal} are the gas volumes released by the biomass char and coal, respectively, and x is the ratio of addition of the biomass char.

RESULTS AND DISCUSSION

Effects of Biomass Char Type and Ratio

The calculated and experimental CH_4 and overall gas yields from the co-hydrogasification of coal with different types of biomass char at 1073 K and 4 MPa are shown in Fig. 2. It was found that the CH_4 and overall gas yields shared a similar tendency, so the overall gas yield was chosen to be discussed in this work. Figure 2 shows that different biomass char additives had different effects on the gas yield. With the addition of SG char, the experimental gas yield showed almost no improvement compared with the calculated values. In contrast, the gas yield decreased to a certain extent, except for the condition of 20% SG char addition. Compared with SG char, both SD char and WS char had obvious effects on the gas yield at various biomass char addition ratios. For SD char, the promoting effect decreased with increasing char addition, and the optimum addition amount was 10%, with an improvement of 16.7% of the gas yield. For WS char, the promoting effect increased at first, and then it decreased with the increase of char addition, reaching the optimum value at 20% addition ratio, with an improvement in the gas yield of 22.1%.

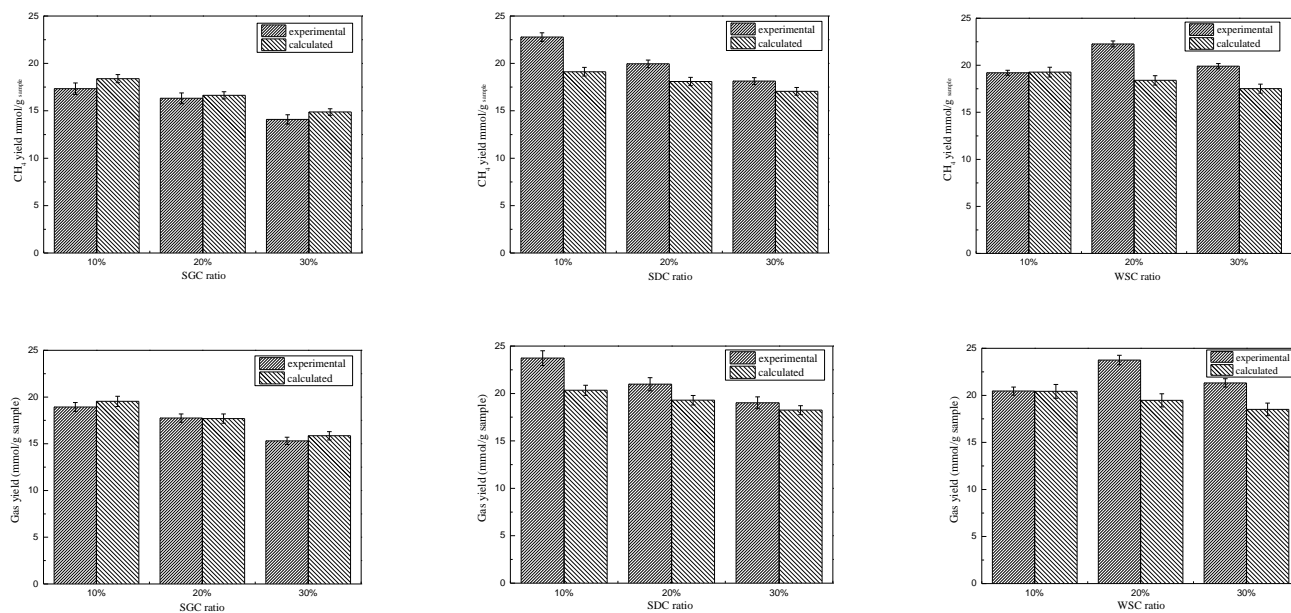


Fig. 2. Calculated and experimental CH₄ and overall gas yields from hydrogasification of coal with various amounts and types of biomass char at 1073 K and 4 MPa

Internal factors affecting the gasification reactivity of raw materials include the volatile matter and mineral and carbon contents (Skodras and Sakellaropoulos 2002; Hattingh *et al.* 2011; Huo *et al.* 2014). In this study, the volatile matter of the biomass chars was not the main factor affecting the gasification reactivity, as the chars obtained experienced a comparatively complete pyrolysis process and most of the volatile matter content (> 90%) was removed. As shown in Table 1, the main components of the biomass chars were fixed carbon and ash, so the main factor could be the mineral matter in the biomass chars. Hydrogasification experiments of coal with various types of biomass ash were conducted to further study the effect of mineral matter; the results are shown in Fig. 3.

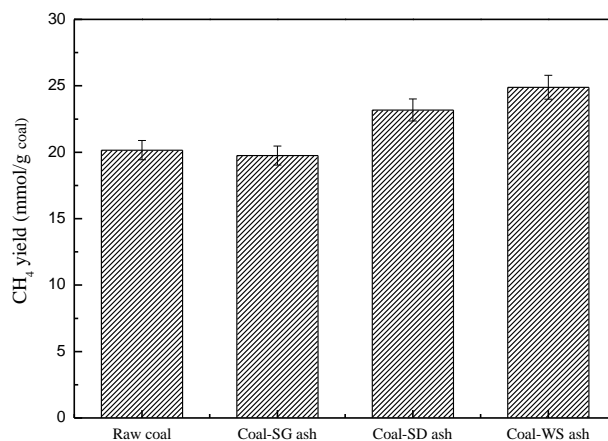


Fig. 3. CH₄ yield of hydrogasification of coal with biomass ash at 1073 K and 4 MPa

The ash loadings were 17.9% SG ash, 5.1% WS ash, and 2.1% SD ash, consistent with the ash content in the biomass char (20% SG char, 20% WS char, 10% SD char). The ashes of SD char and WS char improved the gasification of coal noticeably, but the SG ash did not show a catalytic effect, consistent with results in Fig. 2. The results demonstrated that the AAEM species in biomass char was the main reason for the improvement in the reactivity of carbon materials.

The AAEM species in the ash, such as sodium, potassium, calcium, and magnesium, had catalytic effects on coal gasification, which has been extensively studied (Kühn and Plogmann 1983; Kopyscinski *et al.* 2014). As shown in Table 2, the SG char contained more AAEM species than the others; it can be inferred that the reactivity of samples with SG char should be higher than those with SD char and WS char, but the results indicated the opposite. This phenomenon could be explained by the high chlorine content in the SG char.

The AAEM species in SG char are mostly in the form of chlorides, and the melting points of most chlorides are lower than 1073 K. Therefore, most of the AAEM species in the SG char were released from the sample in the experiment at 1073 K, causing the SG char to lose some of its catalytic effect, which is consistent with the results in Fig. 2a and Fig. 3. The FAAS results showed that K and Na content in the three kinds of residues were decreased by 83.67%, 84.91%, and 77.43%, respectively. The release of AAEM species in SG char is the main reason for losing the catalytic effect.

It was found that the optimum addition amount of SD char differed from that of WS char. With the same amount of char addition (10%), the experimental gas yield of the sample with SD char was higher than that with WS char, which was probably caused by the high content of Si species in WS char, as shown in Table 2. In the process of the catalytic gasification of coal, the Si content in sample is the main reason for the deactivation of catalysis (Bruno *et al.* 1988). With 10% WS char, most of the AAEM species reactor with Si and inactivated the AAEM species, increasing the addition of WS char, the remained AAEM species could have catalytic effect on reactivity.

One reason for the high catalytic effect of 10% SD char is the high content of Ca species. Wang *et al.* (2010) studied the influence of calcium species on the potassium-catalyzed steam gasification of coal and found that the addition of calcium could reduce the inactivation of potassium catalysis. Potassium and sodium species can catalyze the gasification of carbon materials excellent because of the low content of Si species and high content of Ca in SD char. The Ca would first react with Si, decreasing the amount of Si, so that more K and Na would be present to promote activation.

With the increase of char amount, the synergetic effect decreased, as show in Fig. 2. It can be inferred that the biomass char had both promoting and inhibiting effects on the hydrogasification reactivity of the samples. The char hindered the contact of coal with H₂ and the inhibiting effect was enhanced. On the other hand, the AAEM species had a catalytic effect on gasification reactivity. In comprehensive consideration, the synergetic effect decreased.

The SEM analysis results of residues with different addition of chars are shown in Fig. 4. It can be found that the chars attach on the surface of coal, which is the main reason of inhibiting effect on gasification reactivity.

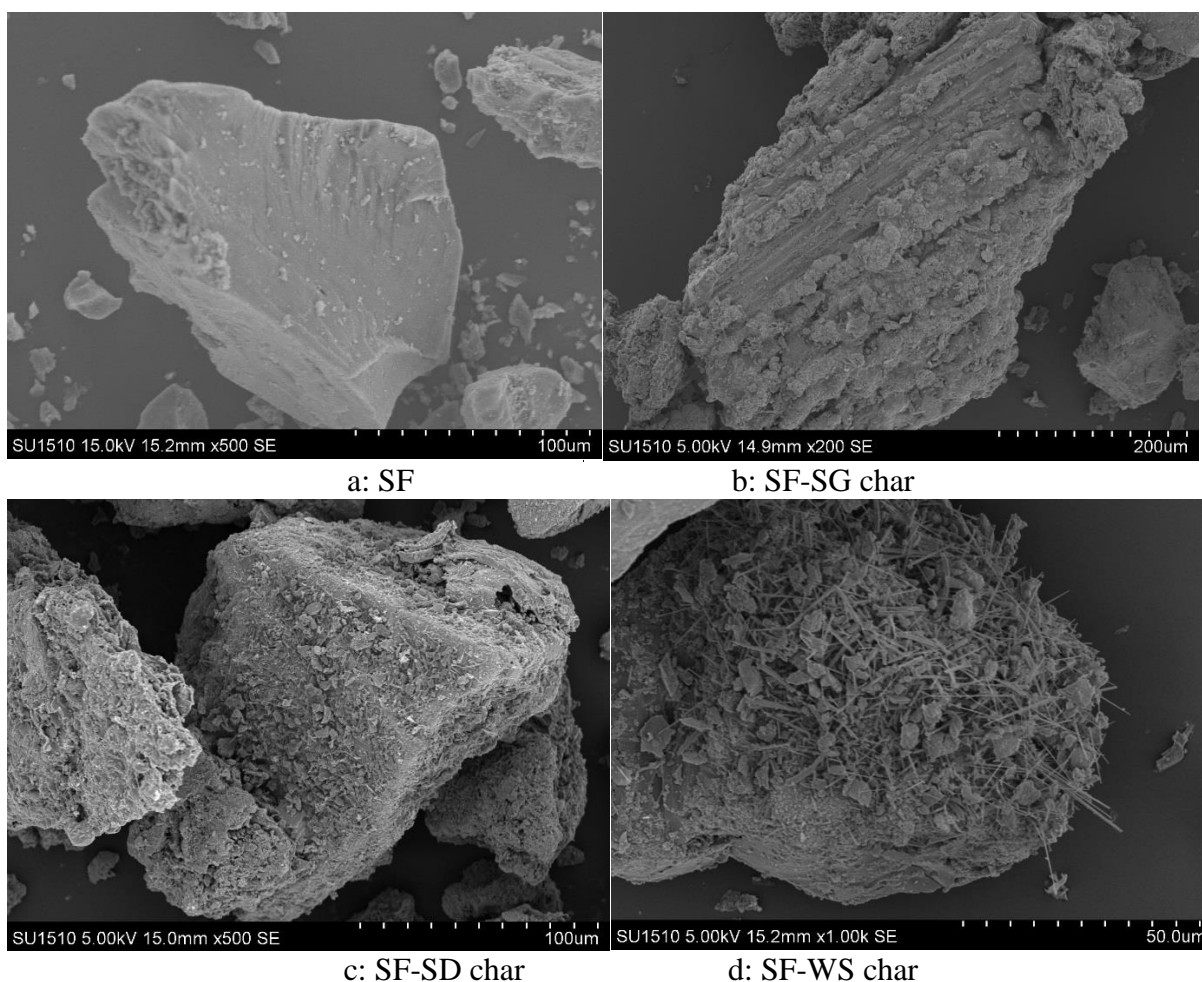


Fig. 4. SEM photographs of residues

CH_4 is the target gas product of the hydrogasification of carbon materials. The CH_4 release rates under different conditions are shown in Fig. 5. The CH_4 release rate curve of raw coal hydrogasification shows that the two peaks on the curve represent the two main stages of coal hydrogasification.

As stated above, the first stage is pyrolysis of coal with the release of volatile matter, and the second stage is the hydrogasification of char. Figure 5a shows that with the addition of SG char, pyrolysis was inhibited because the SG char was attached to the surface of coal as shown in Fig. 4b, preventing the release of volatile matter. In the second stage, there was no noticeable promoting effect on the release rate of CH_4 , which was correlated with Fig. 2a. Figure 5b shows that 10% SD char enhanced the CH_4 release rate to the greatest extent, as did 20% WS char, as shown in Fig. 5c.

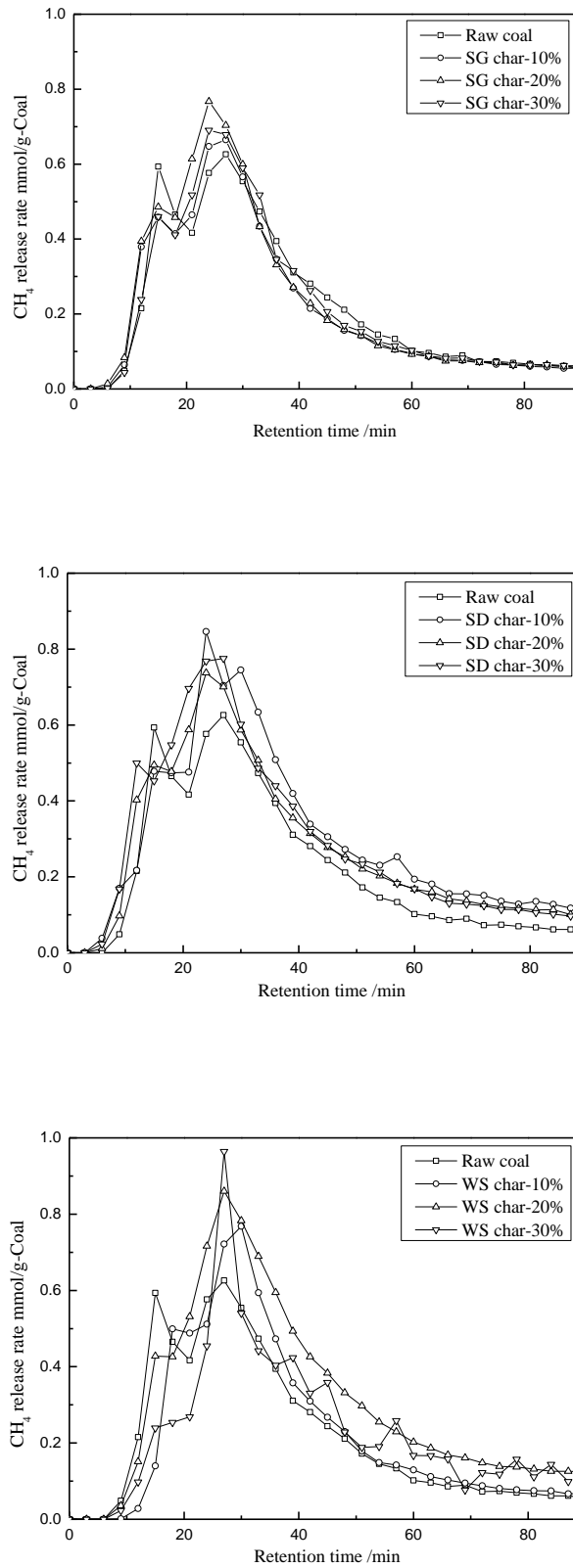


Fig. 5. CH₄ release rate of hydrogasification of coal with various amounts and types of biomass char

Effect of Hydrogasification Temperature

The gasification temperature, an important factor in the gasification process, is one of the essential operating parameters in industry and has significant effects on the gas product composition, carbon conversion, and tar decomposition. To investigate the effect of the gasification temperature on the hydrogasification behavior of coal with the three different biomass chars, experiments were conducted at temperatures of 973, 1023, and 1073 K with a constant pressure of 4 MPa. The addition amounts of the three biomass chars were 20% SG char, 10% SD char, and 20% WS char, which were previously determined to be the optimum amounts. The results are shown in Fig. 6.

Figure 6a shows the experimental gas yields and the calculated values from the hydrogasification of coal with 20% SG char. The gas yields increased with increasing gasification temperature because of the high gasification reactivity of carbon materials at high temperature. At 973 K, the experimental gas yield was increased by 15.7% compared with the calculated value. At 1023 and 1073 K, the improvements were 1.9% and 0.3%, respectively, which means that the synergetic effect at low temperature was much higher than that at high temperature. As stated above, most of the AAEM species in SG were in the form of chloride, which is easily released from the samples at high temperature. At low temperature, the AAEM species remained in the samples and promoted the gasification reactivity of the materials. The synergetic effect at 973 K supports this statement.

Compared with samples with SG char addition, the samples with SD char and WS char showed an opposite trend of gasification reactivity at various temperatures, as shown in Fig. 6b and Fig. 6c. The gas yields of samples with SD char were improved by 4.5% at 973 K, 7.0% at 1023 K, and 16.7% at 1073 K, whereas for samples with WS char addition, the gas yields were improved by 8.6% at 973 K, 16.9% at 1023 K, and 22.1% at 1073 K. With increasing temperature, the synergetic effects were more pronounced because the catalytic activation of AAEM species in SD char and WS char increased.

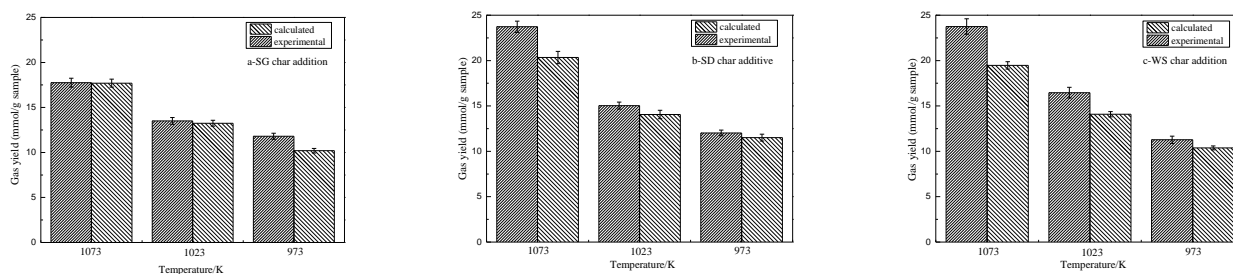


Fig. 6. Calculated and experimental gas yields at various temperatures

Effect of Hydrogasification Pressure

The main reaction in the hydrogasification process of carbon materials is shown in Eq. 2:



This reaction is a volume-reducing reaction, so in the hydrogasification process, application of pressure is necessary to enhance the gasification reactivity of carbon materials. Experiments were conducted at different pressures (0.1, 2, and 4 MPa), and the temperature was kept at 1073 K. The amounts of biomass char were the same as in the previous section. Figure 7 shows the experimental and calculated gas yields from the hydrogasification of samples at various pressures.

The experimental gas yields of samples increased with increasing pressure, which revealed that high pressure promoted the hydrogasification reactivity of materials. As shown in Fig. 7a, the effect of SG char varied with pressure. At high pressure (4 MPa), the experimental gas yield showed almost no improvement compared with the calculated value. This means that the promoting effect and inhibition effect reached a balance, so there was no noticeable synergetic or inhibiting effect observed in the experiments.

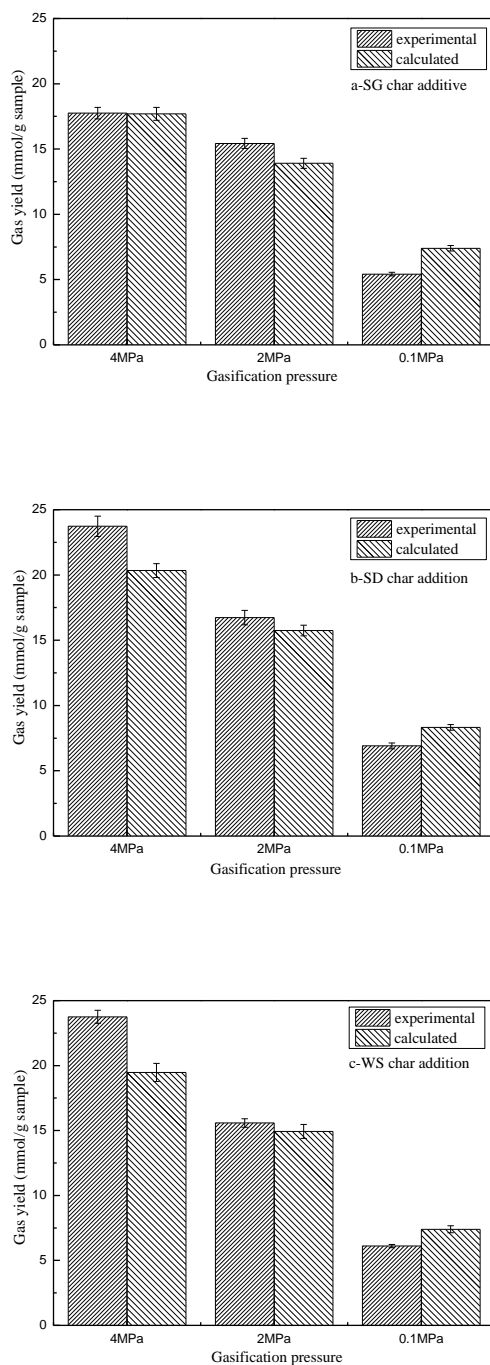


Fig. 7. Calculated and experimental gas yields at various pressures

At 2 MPa, a synergetic effect was observed. The experimental gas yield was increased by 10.9% compared with the calculated value. At 0.1 MPa, the experimental gas yield was reduced by 26.7% compared with the calculated value, which means that the addition of SG char had an inhibiting effect. Three different effects of SG char at various pressures revealed the existence of both a promoting effect and an inhibiting effect. At 0.1 MPa, the hydrogasification reactivity of the sample was weak, and the main reaction occurred in the sample was pyrolysis of raw materials. With the addition of SG char, the release of volatile matter from the coal was inhibited as shown in Fig. 4. At 2 MPa, the reaction of hydrogasification was enhanced, the AAEM species in the SG char had a catalytic effect on the hydrogasification of samples, and the promoting effect was stronger than the inhibiting effect. Overall, the sample showed synergetic effects.

Figure 7b shows the hydrogasification behavior of samples with the addition of SD char at various pressures. At 0.1 MPa, a similar phenomenon was observed as shown in Fig. 7a. The experimental gas yield decreased by 17.1% compared with the calculated value, which confirmed that the existence of biomass chars inhibited the gasification reactivity of coal. Similar results are shown in Fig. 7c.

Both promoting and inhibiting effects of biomass ash on hydrogasification were observed. The char was found to inhibit the coal devolatilization due to pore blockage. The overall mechanism can be elaborated by a scheme as shown in Fig. 8.

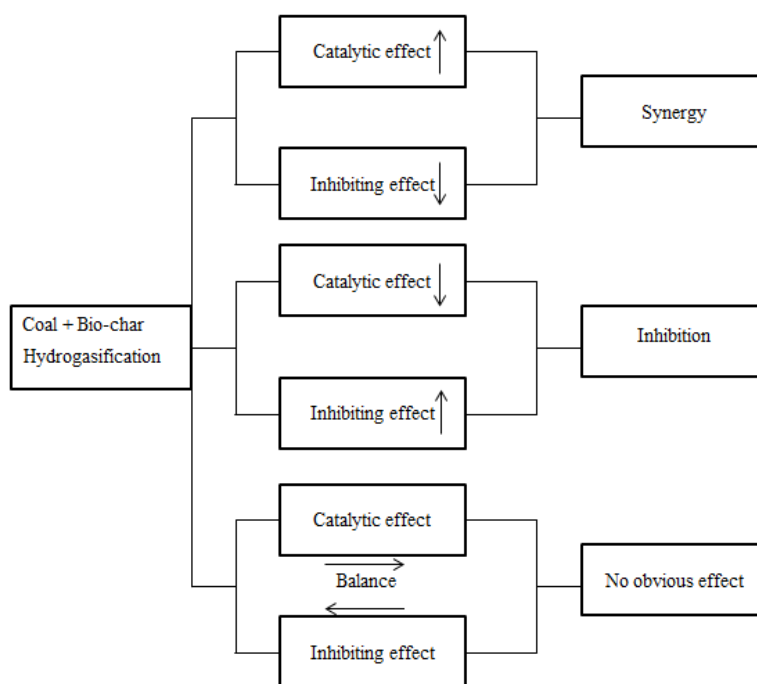


Fig. 8. Scheme of synergy and inhibition of biomass char in hydrogasification

CONCLUSIONS

1. Both synergetic effects and inhibiting effects were observed in the hydrogasification of coal with biomass char at different temperatures and pressures.

2. The gasification experiments revealed that the AAEM species in the biomass char played an important role in this synergetic effect.
3. High gasification temperature and pressure led to higher gasification reactivity.
4. At low pressure of 0.1 MPa, the addition of biomass char inhibited the release of volatile matter, which is the main factor of inhibiting effect.
5. At 1073 K and 4 MPa, for Shenfu coal, the optimum addition amounts are 20% SG char, 10% SD char, and 20% WS char.

ACKNOWLEDGEMENTS

This work was partially supported by the National Natural Science Foundation of China (Grant 21176078) and the National High Technology Research and Development of China (863 program, 2012AA053101).

REFERENCES CITED

- Brown, R. C., Liu, Q., and Norton, G. (2000). "Catalytic effects observed during the co-gasification of coal and switchgrass," *Biomass & Bioenergy* 18(6), 499-506. DOI: 10.1016/S0961-9534(00)00012-X
- Bruno, G., Buroni, M., Carvani, L., Piero, G. D., and Passoni, G. (1988). "Water-insoluble compounds formed by reaction between potassium and mineral matter in catalytic coal gasification," *Fuel* 67(1), 67-72. DOI: 10.1016/0016-2361(88)90014-2
- Castaldi, M. J., and Doohar, J. P. (2007). "Investigation into a catalytically controlled reaction gasifier (CCRG) for coal to hydrogen," *Int. J. Hydrogen Energy* 32(17), 4170-4179. DOI: 10.1016/j.ijhydene.2007.06.014
- Ding, X. K., Zhang, Y. F., Zhang, T. K., Tang, J., Xu, Y., and Zhang, J. (2013). "Effect of operational variables on the hydrogasification of inner mongolian lignite semicoke," *Energy Fuel* 27(8), 4589-4597. DOI: 10.1021/ef4007092
- Hattingh, B. B., Everson, R. C., Neomagus, H. W. J. P., and Bunt, J. R. (2011). "Assessing the catalytic effect of coal ash constituents on the CO₂ gasification rate of high ash, South African coal," *Fuel Process. Technol.* 92(10), 2048-2054. DOI: 10.1016/j.fuproc.2011.06.003
- Hong, B. Q., Wang, X. J., Zhou, Z. J., and Yu, G. S. (2013). "A comparison of the gas-product-release characteristics from coal pyrolysis and hydrogasification," *Energy Technol-Ger* 1(8), 449-456. DOI: 10.1002/ente.201300052
- Huo, W., Zhou, Z. J., Chen, X. L., Dai, Z. H., and Yu, G. S. (2014). "Study on CO₂ gasification reactivity and physical characteristics of biomass, petroleum coke and coal chars," *Bioresour Technol.* 159, 143-149. DOI: 10.1016/j.biortech.2014.02.117
- Jeong, H. J., Park, S. S., and Hwang, J. (2014). "Co-gasification of coal-biomass blended char with CO₂ at temperatures of 900-1100°C," *Fuel* 116, 465-470. DOI: 10.1016/j.fuel.2013.08.015
- Kopyscinski, J., Lam, J., Mims, C. A., and Hill, J. M. (2014). "K₂CO₃ catalyzed steam gasification of ash-free coal. Studying the effect of temperature on carbon conversion and gas production rate using a drop-down reactor," *Fuel* 128, 210-219. DOI:

- 10.1016/j.fuel.2014.03.014
- Krerkkaiwan, S., Fushimi, C., Tsutsumi, A., and Kuchonthara, P. (2013). "Synergetic effect during co-pyrolysis/gasification of biomass and sub-bituminous coal," *Fuel Processing Technology* 115, 11-18. DOI: 10.1016/j.fuproc.2013.03.044
- Kühn, L., and Plogmann, H. (1983). "Reaction of catalysts with mineral matter during coal gasification," *Fuel* 62(2), 205-208. DOI: 10.1016/0016-2361(83)90199-0
- Lee, S. H., Lee, J. G., Kim, J. H., and Choi, Y. C. (2006). "Hydrogasification characteristics of bituminous coals in an entrained-flow hydrogasifier," *Fuel* 85(5-6), 803-806. DOI: 10.1016/j.fuel.2005.08.039
- Li, S., Chen, X., Liu, A., Wang, L., and Yu, G. (2014). "Study on co-pyrolysis characteristics of rice straw and Shenfu bituminous coal blends in a fixed bed reactor," *Bioresour. Technol.* 155, 252-7. DOI: 10.1016/j.biortech.2013.12.119
- Li, S., Chen, X., Wang, L., Liu, A., and Yu, G. (2013). "Co-pyrolysis behaviors of saw dust and Shenfu coal in drop tube furnace and fixed bed reactor," *Bioresour. Technol.* 148, 24-9. DOI: 10.1016/j.biortech.2013.08.126
- Masnadi, M. S., Grace, J. R., Bi, X. T., Ellis, N., Lim, C. J., and Butler, J. W. (2015). "Biomass/coal steam co-gasification integrated with in-situ CO₂ capture," *Energy* 83, 326-336. DOI: 10.1016/j.energy.2015.02.028
- Minchener, A. J. (2005). "Coal gasification for advanced power generation," *Fuel* 84(17), 2222-2235. DOI: 10.1016/j.fuel.2005.08.035
- Murakami, K., Arai, M., and Shirai, M. (2000). "Hydrogasification of Loy Yang brown coal by ion-exchanged nickel species," *Energ Fuel* 14(6), 1240-1244. DOI: 10.1021/Ef000099v
- Pu, G., Zhu, W., Zhou, H., Liu, Y., and Zhang, Z. (2015). "Kinetics of co-gasification of low-quality lean coal and biomass," *BioResources* 10(2), 2773-2782. DOI: 10.15376/biores.10.2.2773-2782
- Quan, C., Xu, S., An, Y., and Liu, X. (2014). "Co-pyrolysis of biomass and coal blend by TG and in a free fall reactor," *Journal of Thermal Analysis and Calorimetry* 117(2), 817-823. DOI: 10.1007/s10973-014-3774-7
- Radović, L. R., Walker Jr, P. L., and Jenkins, R. G. (1983). "Importance of carbon active sites in the gasification of coal chars," *Fuel* 62(7), 849-856. DOI: 10.1016/0016-2361(83)90041-8
- Rizkiana, J., Guan, G. Q., Widayatno, W. B., Hao, X. G., Li, X. M., Huang, W., and Abudula, A. (2014). "Promoting effect of various biomass ashes on the steam gasification of low-rank coal," *Applied Energy* 133, 282-288. DOI: 10.1016/j.apenergy.2014.07.091
- Sheth, A. C., Sastry, C., Yeboah, Y. D., Xu, Y., and Agarwal, P. (2004). "Catalytic gasification of coal using eutectic salts: reaction kinetics for hydrogasification using binary and ternary eutectic catalysts," *Fuel* 83(4-5), 557-572. DOI: 10.1016/j.fuel.2003.08.016
- Skodras, G., and Sakellaropoulos, G. P. (2002). "Mineral matter effects in lignite gasification," *Fuel Process. Technol.* 77, 151-158. DOI: 10.1016/S0378-3820(02)00063-2
- Tomeczek, J., and Gil, S. (2010). "The kinetics of coal chars hydrogasification," *Fuel Process. Technol.* 91(11), 1564-1568. DOI: 10.1016/j.fuproc.2010.06.003

Wang, J., Yao, Y., Cao, J., and Jiang, M. (2010). "Enhanced catalysis of K_2CO_3 for steam gasification of coal char by using $Ca(OH)_2$ in char preparation," *Fuel* 89(2), 310-317. DOI: 10.1016/j.fuel.2009.09.001

Yan, L., Yue, G., and He, B. (2015). "Exergy analysis of a coal/biomass co-hydrogasification based chemical looping power generation system," *Energy* 93, 1778-1787. DOI: 10.1016/j.energy.2015.10.042

Article submitted: April 10, 2016; Peer review completed: May 29, 2016; Revised version received: August 26, 2016; Accepted: August 28, 2016; Published: September 7, 2016.

DOI: 10.15376/biores.11.4.9002-9016