1 **Experimental study on steam gasification of coal using molten**
2 **blast furnace slag as heat carrier for producing**
3 **hydrogen-enriched syngas**

4 Wenjun Duan, Qingbo Yu*, Tianwei Wu, Fan Yang, Qin Qin

5 School of Materials and Metallurgy, Northeastern University, No 11, Lane 3, Wenhua
6 Road, He Ping District, Shenyang 110819, Liaoning, People's Republic of China.

7 *Corresponding author information:

8 Telephone/Fax: +86-024-83672216.

9 E-mail addresses: duanwenjn@163.com (W. J. Duan)

10 yuqb@smm.neu.edu.cn (Q. B. Yu)

11 Mailing address: P.O, Box 345, Northeastern University, No. 11, Lane 3, Wenhua
12 Road, Heping District, Shenyang, Liaoning, P. R. China.

13

Abstract

The new method for producing hydrogen-enriched syngas (HRG) by steam gasification of coal using molten blast furnace slag (BFS) as heat carrier was established. In order to achieve the HRG production, a gasification system using this method was proposed and constructed. The carbon gasification efficiency (CE), hydrogen yield (YH_2) and cold gasification efficiency (CGE) in the molten slag reactor were measured, and the effects of temperature, S/C (steam to coal) ratio and coal type on the reaction performance were accessed. The results indicated that the preferred temperature was 1350°C , which ensured the miscibility of coal-steam-slag, the diffusion of reactant in molten BFS as well as recovering waste heat. The optimal S/C ratio was 1.5~2.0 for producing HRG. Under these conditions, the hydrogen fraction was higher than 63% and the gas yield reached to $1.89 \text{ Nm}^3/\text{kg}$. The CE and CGE were higher than 96% and 102%, respectively. The YH_2 also reached to $1.20 \text{ Nm}^3/\text{kg}$. Meanwhile, different types of coal were successfully gasified in molten BFS reactor for producing HRG. The proposed method enhanced the gasification efficiency of different types of coal, recovered the BFS waste heat effectively, and had important guidance for industrial manufacture.

Keywords:

Hydrogen-enriched syngas; Molten blast furnace slag; Waste heat; Steam gasification; Heat carrier

1. Introduction

Hydrogen was a very versatile environmental energy carrier and the development of cheap and clean hydrogen generation technology had been the most hot research topic [1, 2]. The method of steam gasification with fossil fuels or renewable to produce hydrogen was widely accepted [3, 4]. However, for steam gasification process, some key reactions were intensely endothermic reactions and demanded a large amount of energy [5-7]. In general, the energy was provided by fossil fuel or syngas combustion. Meanwhile, a certain amount of CO₂ was produced in steam gasification process and not friendly for the environment [8, 9]. Therefore, it was essential to find a reasonable energy supply to achieve the environmental and economic benefits in steam gasification process for producing hydrogen.

As we all know, iron and steel industry was an energy-intensive industry, which accounted for approximating 5% of the total energy consumption with a waste heat recovery rate of only 17% [10-12]. BFS was exhausted at extremely high temperature (about 1500-1600°C), and the energy carried was about 1700 MJ/t_{slag}. For example, in 2013, the crude steel production reached up to 822 million tons in China, which meant that the waste heat of hot slag was equivalent to 14.8 million tons standard coal [13]. Therefore, establishing an integrated system of recovering BFS waste heat to provide the energy needed for the steam gasification process was necessary. In the theoretical analysis, Ishida [14] established the enthalpy-exergy diagram to analyze the BFS waste heat recovery. Akiyama et al [15] described a feasibility study of recovering BFS heat using nine chemical reactions by enthalpy-exergy diagram method. By this

method, thermodynamic analysis of BFS waste heat recovery system integrated with coal gasification was conducted by Duan et al [16]. The results showed that the exergy efficiency and recycling efficiency of the established system were 52.6% and 75.4%, respectively. The exergy loss of the integrated system was only 620.0 MJ/t_{slag}. Meanwhile, the thermodynamic analysis of steam gasification using BFS as heat carrier and recycling its waste heat to produce HRG were investigated by Duan et al [12, 17]. The results suggested that the preferred condition for HRG from Datong coal was achieved at 775°C, atmospheric pressure and S/C ratio of 2.0-3.0. In experimental studies, Luo et al [18] established a continuous moving-bed biomass gasification reactor to evaluate the feasibility of recovering BFS particles waste heat and producing HRG at 1000°C. Zhao [19] investigated the possibility of producing the combustible gas from municipal solid waste using BFS waste heat. In his study, the effects of temperature, gasifying agent and BFS particles on the gas production were studied at 600-900°C. Sun et al [20] also investigated the characteristics of biomass gasification and syngas release behavior using hot slag at the low temperature (200-450°C). The syngas (0.149 L CO, 0.036 L H₂ and 0.069 L CH₄) could be produced by per gram of wheat straw when the biomass was mixed with slag. Obviously, the current methods of producing hydrogen by steam gasification using BFS waste heat were entirely feasible. But these methods were only limited to using slag particles at relatively low temperature. However, for BFS waste heat, the high-grade waste heat mainly concentrated in molten slag at 1250°C ~ 1600°C. The process of hydrogen production by steam gasification using molten BFS as heat

carrier was never referred to and lack of comprehensive study. Therefore, it was necessary to investigate the steam gasification process using molten BFS as heat carrier, which would be more benefit for hydrogen production and recovering high-grade waste heat.

In the present study, the approach for steam gasification of coal in molten BFS to produce HRG was proposed and implemented. The effects of temperature, S/C ratio and coal type on steam gasification reaction were investigated, so as to obtain the optimal operation parameters and guide the industrial production.

2. Materials and methods

2.1 Feedstock

Five types of coal (Datong (DT) coal, Fuxin (FX) coal, Fushun (FS) coal, Shennan (SN) coal and Dezhou (DZ) coal) were obtained from various big coal mines in Northern China for gasification experiments to produce HRG. Their compositions and properties were shown in [Table 1](#). The ultimate analysis of the sample was conducted using a CHNS/O Analyzer, Perkin Elmer PE 2400 series II. The proximate analysis of the sample was conducted using an automatic coal proximate analyzer. During preparing coal samples, the first step crushing coal pieces with a hammer and crusher for the appropriate size. Then these crushed particles were segregated into about 75 μm using a series of sieve shakers.

BFS from an iron and steel company was used in experiments as heat carrier with chemical compositions of 41.21 mass% CaO, 34.38 mass% SiO₂, 11.05 mass% Al₂O₃, 8.22 mass% MgO, 2.78 mass% Fe₂O₃, 0.35 mass% TiO₂ and some minor constituents

of sulfur, manganese and phosphor oxides. Its chemical compositions were analyzed by X-ray fluoroscopy (XRF, SE-Explore, Bruker). In the experiment, the pulverized coal was conveyed by carrier gas and the reactor should be replenished with shielding gas before the experiment. The carrier gas and shielding gas used in experiments were N₂ with 99.99% purity.

Table 1 The proximate and elemental analysis of the coal

Coal	DT	FX	FS	SN	DZ
Proximate analysis (wt%)					
Moisture, wt%	9.05	3.13	1.83	2.30	4.96
Volatile matter, wt%	38.38	32.78	28.72	26.38	4.82
Fixed carbon, wt%	38.42	34.79	20.81	22.85	19.11
Ash, wt%	14.15	29.30	48.64	48.47	71.11
Ultimate analysis (wt%)					
Carbon	64.53	52.27	39.05	42.59	21.57
Hydrogen	3.746	4.204	3.489	3.379	0.710
Nitrogen	0.956	1.09	1.13	0.74	0.19
Sulfur	0.561	1.210	0.619	0.967	0.457
Oxygen	7.007	8.796	5.242	1.554	1.003

2.2 Experimental system

The experiment system of steam gasification of coal using molten BFS as heat carrier for producing HRG was established, as shown in Fig. 1. The system was composed of seven parts: feeding system, primary reactor system, temperature

measurement system, gas purification system, flow measurement system, gas composition analysis system and off-gas treatment system.

1. N₂ Cylinder; 2. Steam Generator; 3. Screw Feeder; 4. Gasometer; 5. Control Cabinet;
6. Electric Furnace; 7. Temperature Measuring; 8. Heat Exchanger; 9. Drier; 10.
Computer; 11. Exhaust; 12. Gas Analyzer.

A. Feeding System; B. Temperature Measurement System; C. Flow Measurement
System; D. Off-gas Treatment System; E. Primary Reactor System; F. Gas Purification
System; G. Gas Composition Analysis System.

Fig. 1 The schematic diagram of the experimental apparatus

The primary reactor system was the key part of the integrated system, as shown in Fig. 2. The high purity corundum with high corrosion resistance was adopted as the reactor so as to perform the reaction for a long time. The reactor, which was externally heated in an electric furnace (SG1-15-16), had a height of 100 cm and a volume of 196 cm³. Meanwhile, the feeding system was also a key part to ensure the successful experiment. The powder feeder (TWLP 15) was adopted in the feeding

system, and the rate was controlled in the range of 2.0 g/min ~ 25 g/min. The bulk density of the pulverized coal in the powder feeder was about 0.74 g/cm³. At last, the portable gas analyzer (Gasboard-3100P) was used to ensure the accuracy of the experimental results.

Fig. 2 The schematic diagram of the primary reactor

2.3 Experimental procedure

In a typical test, the suitable height of the molten BFS was about 300 mm for the gasification reaction [21]. Therefore, about 1.8 kg BFS particles sample was crushed and ground to about 2 mm and then put into the reactor. The loaded reactor was placed in the electric furnace and heated to the target temperature, and then kept it about 2 hours so as to the temperature remain stable and evenly distribute. The rated power, rated voltage and rated temperature of the electric furnace were 15 KW, 380V and 1600°C, respectively. The reactor was insulated with glass wool material to maintain the temperature of gasification reaction in molten BFS. Furthermore, there was a temperature controller with a thermocouple (type K) placed into the reactor to

control and record the temperature. When steam stream and the target temperature were stable after about half an hour, the powder feeder worked and the pulverized coal was carried into the reactor by N₂. At this time, the coal gasification reaction with steam was carried out in molten BFS and produced the HRG. The composition of syngas was recorded by gas analyzer, and the powder feeder was closed after the gas composition being stable for 30 minutes. The gasification reaction finished when the content of hydrogen reached to zero, and the next experiment could be carried out by repeating the above steps. The operating conditions of the gasification experiment were shown in Table 2.

2.4 Method of data processing

The carbon gasification efficiency (CE) was calculated by [22]:

$$CE(\%) = \frac{12(CO+CO_2+CH_4)Y_{G,daf}}{22.4C_{daf}} \times 100\% \quad (1)$$

where, $Y_{G,daf}$, $(CO+CO_2+CH_4)$ and C_{daf} were the gas yield, volumetric fraction of syngas compositions and mass of carbon in coal on dry and ash free basis, respectively.

The hydrogen yield (Y_{H_2}) was calculated by [22]:

$$Y_{H_2}(\text{mol/kg}) = \frac{n_{H_2}}{m_{\text{coal}}} \quad (2)$$

where, n_{H_2} was the mole of the hydrogen, m_{coal} was the mass of the coal.

The lower heating value (LHV) of dry syngas was defined as [2]:

$$LHV_{\text{syngas}}(\text{MJ/Nm}^3) = (108.0H_2 + 126.4CO + 358.2CH_4) \times 10^{-3} \quad (3)$$

The higher heating value (HHV) of the coal was calculated with a correlation

presented in the literature [23, 24]:

$$\text{HHV}_{\text{coal}}(\text{MJ/kg}) = 0.33(\text{Volatiles matter}) - 0.11(\text{Moisture}) + 0.35(\text{Fixed carbon}) - 0.03(\text{Ash}) \quad (4)$$

The lower heating value of the coal could be estimated by [25]:

$$\text{LHV}_{\text{coal}}(\text{MJ/kg}) = \text{HHV}_{\text{coal}} - 9m_{\text{H}}(h_{\text{fg}}) \quad (5)$$

where, m_{H} was the mass fraction of hydrogen in the coal, and h_{fg} was the enthalpy of vaporization of water.

Based on the Eq. (3) and Eq. (5), the cold gasification efficiency (CGE) could be obtained:

$$\text{CGE}(\%) = \frac{\text{LHV}_{\text{syngas}}(\text{MJ/Nm}^3) \times V_{\text{syngas}}(\text{Nm}^3/\text{kg})}{\text{LHV}_{\text{coal}}(\text{MJ/kg})}$$

(6)

Table 2 The operating conditions in the gasification system

Particle size (μm)	Coal Type	Temperature ($^{\circ}\text{C}$)	S/C ratio	Bed height (mm)
75		1200		
	DT coal	1250	1:1	
	FX coal	1300	1.5:1	
	FS coal	1350	2:1	300
	SN coal	1400	2.5:1	
	DZ coal	1450	3:1	
		1500		

3. Results and discussions

Since there were no references regarding the production of HRG by steam

gasification of coal in molten BFS, the characteristics of steam gasification in molten BFS were firstly studied. The steam gasification in molten BFS was successfully carried out and produced a large amount of HRG. Meanwhile, the effects of temperature, S/C ratio and coal type on gasification reaction were discussed, respectively. The optimal operation parameters were obtained for guiding industrial production.

3.1 Effect of the gasification temperature

The temperature could significantly influence the gasification performance by promoting or inhibiting the reaction rate and changing the chemical reaction equilibrium. The effect of the temperature (1200°C ~ 1500°C) on the gasification performance of FS coal was studied with S/C ratio of 2.0 and reactor bed height of 300 mm. As seen in [Table 3](#), with temperature increasing, the carbon residue decreased from 6.15 mol/kg to 0.37 mol/kg and the gas yield increased from 1.73 Nm³/kg to 1.91 Nm³/kg. It was because that higher temperature provided more favorable conditions for thermal cracking and steam reforming of carbon, thus the carbon residue dramatically decreased. Meanwhile, the cracking of volatile matter accelerated at high temperature, which was another reason for changing the gasification performance [\[2\]](#).

The fraction distribution of production syngas related with the reaction temperature was shown in [Fig. 3](#). It could be seen from the picture, the fraction of H₂ and CO₂ decreased steadily with the temperature increasing, but the change of CO fraction was contrary to them. The fraction of CH₄ was infausted with the increasing of

temperature, but the CH₄ was poor and hard to make an impact on gas production.

The gasification performance of FS coal in molten BFS was consistent with Duan's simulation results based on the method of Gibbs free energy minimization [17]. The root of the change was the reverse water gas shift reaction ($\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2$) was significantly stimulated in the molten BFS when the temperature and carbon conversion arrived to some level, compared with the primary water gas reaction ($\text{C}_\text{s} + \text{H}_2\text{O} \rightleftharpoons \text{CO} + \text{H}_2$). In the whole temperature range, the H₂ fraction was higher than 62%, and the combustion gases were higher than 70%. Therefore, the results indicated that producing HRG by the steam gasification of coal in molten BFS was feasible.

Table 3 Gasification performance of FS coal under different operating temperatures (S/C ratio = 2.0)

Temperature (°C)	Carbon residue (mol/kg)	Gas Yield (Nm ³ /kg)	H ₂ Yield (Nm ³ /kg)	Gas LHV (MJ/Nm ³)
1200	6.15	1.73	1.14	9.73
1250	4.23	1.81	1.18	9.94
1300	2.66	1.86	1.19	10.11
1350	1.25	1.89	1.20	10.24
1400	0.73	1.90	1.20	10.34
1450	0.42	1.91	1.19	10.42
1500	0.37	1.91	1.19	10.49

Fig. 3 The effect of temperature on syngas fraction distribution of FS coal gasification (S/C ratio = 2.0)

The characteristics of CE, CGE and YH₂ with different temperatures were shown in **Fig. 4**. As the temperature increased from 1200°C to 1500°C, CE and CGE increased firstly and then remained relatively stable, especially the CE increased from 81.10% to 98.88%, while the YH₂ increased from 50.90 mol/kg to 53.52 mol/kg and then decreased to 53.06 mol/kg. The steam gasification benefited from increasing temperature, but the temperature's contribution slowed down when the temperature was higher than 1350°C. It was because that increasing the reaction temperature could decrease the viscosity of molten BFS, enhance the miscibility of coal-steam-slag as well as the diffusion of reactant in molten BFS [26, 27]. When the viscosity reduced to a certain value, there was no remarkable influence on the miscibility and diffusion in the gasification process because the viscosity of the molten BFS basically kept steady. As can be seen from **Fig. 5**, with the BFS temperature increasing, the viscosity of the slag decreased sharply at the melting temperature and then decreased moderately. The viscosity of molten BFS decreased to be lower than 2.50 Pa·s when

temperature was higher than 1350°C. Based on the experimental experience by Liu [28-30], the viscosity of slag should be usually maintained to be lower than 2.50 Pa·s so as to guarantee the coal gasification reaction process proceeding smoothly and the subsequent processing of the slag (granulating-rotary cup atomizer). Meanwhile, the lower gasification temperature was, the more waste heat of BFS was recovered. Therefore, taking various elements into consideration, such as gasification efficiency, H₂ yield production and waste heat recovery, et al, the optimal operation temperature of steam gasification in molten BFS was controlled around 1350°C.

Fig. 4 The characteristic of CE, CGE and YH₂ with different temperatures (S/C ratio = 2.0)

Fig. 5 The effect of temperature on the viscosity of BFS in the FS coal gasification system

3.2 Effect of the S/C ratio

In order to investigate the effect of S/C ratio on the production of HRG, steam gasification of FS coal in molten BFS was conducted at different ratios (1.0 ~ 3.0) and the results were given in Table 4. As S/C ratio increased from 1.0 to 3.0, gas yield and H₂ yield increased significantly from 1.48 Nm³/kg to 2.03 Nm³/kg, and from 0.95 Nm³/kg to 1.31 Nm³/kg, respectively. Higher S/C ratio resulted in the decrease of carbon residue, which was about 0.46 mol/kg at S/C ratio of 3.0 because higher concentration of steam dramatically enhanced primary water gas reaction ($C_s + H_2O \rightleftharpoons CO + H_2$). Meanwhile, the added steam also enhanced the water gas shift reaction ($CO + H_2O \rightleftharpoons CO_2 + H_2$). It was the reason for that the LHV of syngas showed a slight decreased from 10.98 MJ/Nm³ to 9.70 MJ/Nm³.

Table 4 Gasification performance of FS coal under different S/C ratios (Temperature = 1350°C)

S/C ratio	Carbon residue (mol/kg)	Gas Yield (Nm ³ /kg)	H ₂ Yield (Nm ³ /kg)	Gas LHV (MJ/Nm ³)
1:1	4.93	1.48	0.95	10.98
1.5:1	2.49	1.76	1.10	10.61
2:1	1.25	1.89	1.20	10.24
2.5:1	0.73	1.97	1.27	9.94
3:1	0.46	2.03	1.31	9.70

Fig. 6 showed the variation of syngas fractions with different S/C ratios. The fractions of H₂ and CO₂ showed the obvious increase with the S/C ratio increasing, while CO showed the reverse change trend. The changes resulted from the integrated

effect of primary water gas reaction and water gas shift reaction. It also could be seen from Fig. 7, CE and Y_{H_2} also increased with the S/C ratio increasing. Based on the above analysis, the higher S/C ratio was beneficial to produce HRG, especially increase the content of H_2 . However, did the more steam addition contribute to the coal gasification reaction ?

Fig. 6 The effect of S/C ratio on syngas fraction distribution of FS coal gasification (Temperature = 1350°C)

Fig. 7 The characteristic of CE, CGE and Y_{H_2} with different S/C ratios (Temperature = 1350°C)

As can be seen from Fig. 7, for the CGE, firstly it rose to a peak with the S/C ratio around 1.5, and after that it began to monotonically decrease. It was pointed out that

the change of CGE was mainly caused by the extra steam introduced more than the necessity for gasification [17]. Therefore, although increasing S/C ratio was favorable to produce HRG, the optimal parameter of S/C ratio was 1.5~2.0 considering the energy consumption of the gasification system.

3.3 Effect of the coal type on gasification reaction

In general, the steam gasification of a coal species was affected by its properties such as volatile matter, ash and carbon content, et al. Table 5 showed the gasification performance of the five typical Northern China coals. As shown in Table 5, there was no significant difference on carbon residue for different types of coal, but the production of gas yield and H₂ yield significantly decreased from DT coal to DZ coal in the process of steam gasification in molten BFS. Compared with the production syngas of DT coal, the significant reduction of gas yield and H₂ yield were mainly due to the high content of ash in DZ coal. On analysis, for different types of coal, the steam gasification reaction could proceed smoothly and effectively with the molten BFS as heat carrier.

As shown in Fig. 8, syngas production with high H₂ fraction and relatively lower CO and CO₂ was obtained from the five coal samples. CO₂ fraction was lower than 10% in these five samples, which indicated that the controlling temperature and S/C ratio were applicable. The maximum H₂ fraction (64.26%) was obtained from SN coal, whereas the minimum of H₂ fraction (58.76%) was obtained from DZ coal. These differences were mainly caused by the different chemical compositions of the coals, which were shown in Table 1.

Table 5 Gasification performance of different types of coal (Temperature = 1350°C and S/C ratio = 2.0)

Coal Type	Carbon residue (mol/kg)	Gas Yield (Nm ³ /kg)	H ₂ Yield (Nm ³ /kg)	Gas LHV (MJ/Nm ³)
DT	1.18	2.99	1.81	10.16
FX	1.05	2.50	1.55	10.18
FS	1.25	1.89	1.20	10.24
SN	1.24	1.94	1.24	10.25
DZ	0.84	0.93	0.55	10.03

Fig. 8 The effect of coal type on syngas fraction distribution (Temperature = 1350°C and S/C ratio = 2.0)

According to the above analysis, the steam gasification of coal using molten BFS as heat carrier was a meaningful and effective method, which could resolve the issue of low reaction efficiency, especially for DZ coal gasification reaction, as shown in Fig. 9. So, in the gasification, this method could be applied widely in various types of coal to produce the HRG.

Fig. 9 The characteristic of CE, CGE and YH₂ with different types of coal (Temperature = 1350°C, and S/C = 2.0)

4. Conclusions

The system of producing HRG by steam gasification of coal using molten BFS as heat carrier was proposed. The effects of the gasifier temperature, S/C ratio and coal type on the gasification were investigated. Experimental results showed that the hydrogen yield, gas yield, and hydrogen fraction et al were strongly related with the temperature, S/C ratio. The preferred conditions for HRG from FS coal were achieved at 1350°C and S/C ratio of 1.5~2.0. Under these conditions, the hydrogen fraction was higher than 63% and the gas yield reached to 1.89 Nm³/kg. The CE and CGE were higher than 96% and 102%, respectively. The YH₂ also reached to 1.20 Nm³/kg. By this method, different types of coal were gasified effectively in molten BFS, which effectively solved the utilization of coal.

The results in this work may provide a solution for the problem of recovering the slag waste heat and confirming the technical feasibility of steam gasification of coal using molten BFS as heat carrier.

Nomenclature

n_{H_2} = the mole of the product hydrogen, mol;

m_{coal} = the mass of the coal, kg;

m_{H} = the mass fraction of hydrogen in the coal, %;

h_{fg} = the enthalpy of vaporization of water, MJ/kg.

Abbreviations

BFS = Blast furnace slag

HRG = hydrogen-enriched syngas

DT coal = Datong coal

FX coal = Fuxin coal

FS coal = Fushun coal

SN coal = Shennan coal

DZ coal = Dezhou coal

CE = Carbon gasification efficiency

YH_2 = Hydrogen yield

LHV = Lower heating value

HHV = Higher heating value

CGE = Cold gasification efficiency

Acknowledgements

This research was supposed by The National Natural Science Foundation of China (51274066, 51304048), The National Science Foundation for Post-doctoral Scientists of China (2015M571322), The National Key Technologies R&D Program of China

(2013BAA03B03), The Fundamental Research Funds for the Central Universities
(N130402019).

References

- [1]. Kang K, Azargonhar R, Dalai AK, Wang H. Systematic screening and modification of Ni based catalysts for hydrogen generation from supercritical water gasification of lignin. *Chemical Engineering Journal* 2015; 283: 1019-1032.
- [2]. Wang RP, Huang QX, Lu P, Li WJ, Wang SK, Chi Y, Yan JH. Experimental study on air/steam gasification of leather scraps using U-type catalytic gasification for producing hydrogen-enriched syngas. *International Journal of Hydrogen Energy* 2015; 40: 8322-8329.
- [3]. Xia A, Cheng J, Song WL, Su HB, Ding LK, Lin RC, Lu HX, Liu JZ, Zhou JH, Cen KF. Fermentative hydrogen production using algal biomass as feedstock. *Renewable and Sustainable Energy Reviews* 2015; 51: 209-230.
- [4]. John RP, Anisha GS, Nampoothiri KM, Pandey A. Micro and macroalgal biomass: a renewable source for bioethanol. *Bioresource Technology* 2011; 102: 186-193.
- [5]. Luo SY, Xiao B, Hu ZQ, Liu SM, Guo XJ, He MY. Hydrogen-rich gas from catalytic steam gasification of biomass in a fixed bed reactor: influence of temperature and steam on gasification performance. *International Journal of Hydrogen Energy* 2009; 34: 2191-2194.
- [6]. Tao J, Lu Q, Dong CQ, Du XZ, Dahlquist E. Effects of electric current upon catalytic steam reforming of biomass gasification tar model compounds to syngas. *Energy Conversion and Management* 2015; 100: 56-63.

- 354 [7]. Karnjanakom S, Guan GQ, Asep B, Du X, Hao XG, Samart C, Abudula A.
355 Catalytic steam reforming of tar derived from steam gasification of sunflower
356 stalk over ethylene glycol assisting prepared Ni/MCM-41. *Energy Conversion*
357 *and Management* 2015; 98: 359-368.
- 358 [8]. Mohammad S. Masnadi, John R. Grace, Xiaotao T. Bi, Naoko Ellis, C. Jim Lim,
359 James W. Butler. Biomass/coal steam co-gasification integrated with in-suit CO₂
360 capture. *Energy* 2015; 83: 326-336.
- 361 [9]. Mostafavi E, Mahihey N, Manovic V. Anovel development of mixed
362 catalyst-sorbent pellets for steam gasification of coal chars with in suit CO₂
363 capture. *Catalysis Today* 2014; 237: 111-117.
- 364 [10]. Ma GY, Cai JJ, Zeng WW, Dong H. Analytical research on waste heat recovery
365 and utilization of China's iron & steel industry. *Energy Procedia* 2012; 14:
366 1022-1028.
- 367 [11]. Cahyono RB, Ronzhan AN, Yasuda N, Nomura T, Hosokai S, Kashiwaya Y,
368 Akiyama T. Integrated coal-pyrolysis tar reforming using steelmaking slag for
369 carbon composite and hydrogen production. *Fuel* 2013; 109: 439-444.
- 370 [12]. Duan WJ, Yu QB, Wang K, Qin Q, Hou LM, Yao X, Wu TW. ASPEN Plus
371 simulation of coal integrated gasification combined blast furnace slag waste heat
372 recovery system. *Energy Conversion and Management* 2015; 100: 30-36.
- 373 [13]. Xu B, Lin BQ. Assessing CO₂ emissions in China's iron and steel industry: A
374 dynamic vector autoregression model. *Applied Energy* 2016; 161: 375-386.
- 375 [14]. Ishida M. *Thermodynamic Made Comprehensible* (New York: Nova Science

Publishers Inc., 2002).

[15]. Akiyama T, Oikawa K, Shimada T, Kasai E, Yagi JI. Thermodynamic analysis of thermochemical recovery of high temperature wastes. *ISIJ International* 2000; 40, 286-291.

[16]. Duan WJ, Li P, Lei W, Chen W, Yu QB, Wang K, Qin Q. Thermodynamic analysis of blast furnace slag waste heat-recovery system integrated with coal gasification. *JOM* 2015; 67(5): 1079-1085.

[17]. Duan WJ, Yu QB, Xie HQ, Qin Q, Zuo ZL. Thermodynamic analysis of hydrogen-rich gas generation from coal/steam gasification using blast furnace slag as heat carrier. *International Journal of Hydrogen Energy* 2014; 39: 11611-11619.

[18]. Luo SY, Zhou YM, Yi CJ. Hydrogen-rich gas production from biomass catalytic gasification using hot blast furnace slag as heat carrier and catalyst in moving-bed reactor. *International Journal of Hydrogen Energy* 2012; 37: 15081-15085.

[19]. Zhao LM, Wang H, Qing S, Liu HL. Characteristics of gaseous product from municipal solid waste gasification with hot blast furnace slag. *Journal of Natural Gas Chemistry* 2010; 19: 403-408.

[20]. Sun YQ, Zhang ZT, Seetharaman S, Liu LL, Wang XD. Characteristics of low temperature biomass gasification and syngas release behavior using hot slag. *RSC Advances* 2014; 4: 62105-62114.

[21]. Li P, Yu QB, Qin Q, Liu HX. Adaptability of coal gasification in molten blast furnace slag on coal samples and granularities. *Energy & Fuels* 2011; 25:

398 5678-5682.

399 [22]. Tursun Y, Liu JG, Xu SP, Wei LG, Zuo WJ. Catalytic steam gasification of
400 lignite olivine as solid heat carrier. *Fuel* 2013; 112: 641-645.

401 [23]. Jin H, Lu YJ, Liao B, Guo LJ, Zhang XM. Hydrogen production by coal
402 gasification in supercritical water with a fluidized bed reactor. *International*
403 *Journal of Hydrogen Energy* 2010; 35: 7151-7160.

404 [24]. Shabbar S, Janajreh I. Thermodynamic equilibrium analysis of coal gasification
405 using Gibbs energy minimization method. *Energy Conversion and Management*
406 2013; 65: 755-763.

407 [25]. Majumder AK, Jain R, Banerjee P, Barnwal JP. Development analysis of a new
408 proximate analysis based correlation to predict calorific value of coal. *Fuel* 2008;
409 87(13-14): 3077-3081.

410 [26]. Nouredini H, Zhu D. Kinetics of transesterification of soybean oil. *Journal of*
411 *the American Oil Chemists Society* 1997; 74(11): 1457-1463.

412 [27]. Maneerung T, Kawi S, Wang Chi-Hwa. Biomass gasification bottom ash as a
413 source of CaO catalyst for biodiesel production via transesterification of palm oil.
414 *Energy Conversion and Management* 2015; 92: 234-243.

415 [28]. Liu JX, Yu QB, Guo Q. Experimental investigation of liquid disintegration by
416 rotary cups. *Chemical Engineering Science* 2012; 73: 44-50.

417 [29]. Liu JX, Yu QB, Li P, Du WY. Cold experiments on ligament formation for blast
418 furnace slag granulation. *Applied Thermal Engineering* 2012; 40: 351-357.

419 [30]. Liu JX, Yu QB, Duan WJ, Qin Q. Experimental investigation on ligament

420 formation for molten slag granulation. Applied Thermal Engineering 2014; 73:
421 888-893.
422

423 **TABLE CAPTION**

424 **Table 1** The proximate and elemental analysis of the coal

425 **Table 2** The operating conditions in the gasification system

426 **Table 3** Gasification performance of FS coal under different operating temperatures

427 (S/C ratio = 2.0)

428 **Table 4** Gasification performance of FS coal under different S/C ratios (Temperature

429 = 1350°C)

430 **Table 5** Gasification performance of different types of coal (Temperature = 1350°C

431 and S/C ratio = 2.0)

432

FIGURE CAPTION

Fig. 1 The schematic diagram of the experimental apparatus

Fig. 2 The schematic diagram of the primary reactor

Fig. 3 The effect of temperature on syngas fraction distribution of FS coal gasification

(S/C ratio = 2.0)

Fig. 4 The characteristic of CE, CGE, YH₂ with different temperatures

Fig. 5 The effect of temperature on the viscosity of BFS in the FS coal gasification

system

Fig. 6 The effect of S/C ratio on syngas fraction distribution of FS coal gasification

(Temperature = 1350°C)

Fig. 7 The characteristic of CE, CGE, YH₂ with different S/C ratios

Fig. 8 The effect of coal type on syngas fraction distribution (Temperature = 1350°C

and S/C ratio = 2.0)

Fig. 9 The characteristic of CE, CGE and YH₂ with different types of coal

(Temperature = 1350°C, and S/C = 2.0)