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COAL GASIFICATION CHARACTERISTICS IN A 2MWth SECOND-GENERATION PFB GASIFIER

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ABSTRACT

Coal gasification process and equipment feasibility research were carried out in a 2 MW thermal input pressurized spout-fluid bed pilot-scale gasifier and a long-time-run test was performed to study the effects of operating parameters on coal partial gasification behaviors. The test results have demonstrated the feasibility of the gasifier to provide suitable fuel gas and residual char for downstream system of 2G PFBC-CC. The concentration of methane decreased at higher gasification temperature due to the secondary cracking of methane while the carbon conversion increased, and the concentration of hydrogen increased with an increase of steam flow rate. The main experimental results were compared with those of pilot-scale facilities in the world.

INTRODUCTION

The first-generation PFBC (1G PFBC) is quite success through the commercial demonstration or commercial operation. More researchers have paid particular attention to its high power generation efficiency and environmentally acceptable alternative for coal utilization. The power generation efficiency of 1G PFBC is difficult to surpass 42% due to the limitation of combustion temperature in fluidized bed [1]. The second-generation PFBC (2G PFBC) inherits the advantages of 1G PFBC and Integrated Gasification Combined Cycle (IGCC), which combined the partial gasification of coal to a fuel gas with the residual char burned in a PFB or CFB combustor. The fuel gas from a carbonizer with low heating value is filtered to remove particle and then fired to enhance the inlet temperature of gas turbine. Thus, the power generation efficiency can be promoted substantially and the thermal efficiency achieves 45%-47%. The residual chars combust in a fluidized bed boiler to supply steam [2-3]. At present, the pilot experiment on the technology of 2G PFBC are still being developed in the world, and the relative studies are being carried out by the United States Department of Energy (DOE) and Foster Wheeler Company, the British Coal Research Establishment (CRE), the Japanese Power Development Company and Mitsubishi Heavy Industries (MHI) [4-6]. Based on the successful build of the first 15 MWe 1G PFBC-CC pilot power plant in Jiawang power plant in China, Thermoenergy Engineering Research Institute of Southeast University (TERI, SEU) constructed a 2G PFBC pilot-scale experimental system, including a 2 MWth pressurized spout-fluid bed partial gasifier and a 1 MWth pressurized fluidized bed combustor. The experimental studies on process and facility of a 2 MWth pressurized spout-fluid bed partial gasifier and the experimental results of a long-time-run test will be introduced in this study.

EXPERIMENTAL

Test facility

The schematic diagram of 2 MWth pressurized spout-fluid bed partial gasifier system is shown in Fig. 1. The system is composed of a gasifier, a lock hopper of coal and limestone, a lock hopper of ash and slag, a circulating system of fly ash, a clean system of fuel gas, a combustion system of fuel gas, a boiler and superheater system of steam, a measurement and control system, and a sampling system. Coal and limestone were pressurized in lock hoppers and fed by a star feeder and a transporting injector into the bottom of gasifier through the spout-nozzle. The transporting air was supplied by a compressor. The steam generated from an oil-fired boiler and heated by a superheater, mixed with the air preheated by an air preheater in a mixing chamber and then entered into a wind box as fluidized gas. The other preheated air mixed with the transporting air in the spout tube. The mixing air was considered as the spouting gas and was introduced into bed with coal together. The spout-fluid bed was used for coal partial gasifier. Its external diameter is 1120 mm and total height is 10500 mm. The gasifier was lined with refractory brick and insulating brick. The height of main gasification zone with an internal diameter of 450 mm is 4250 mm while the height of free space zone with an internal diameter of 640 mm is 6500 mm. The fuel gas from gasifier first entered into water-cooled unit and then entered into cyclone separator to remove fly ash. The collected fly ash was sent back into bed by a loop seal. After the flue gas was separated by the primary vertical cyclone separator and the secondary horizontal cyclone separator, it was sampled to analyze. The clean fuel gas combusted in a combustion chamber of fuel gas. The flue gas emission from combustion chamber of fuel gas preheated the air and then entered into atmosphere through a muffler after cooled by spraying water. The residual char was cooled and charged by the water-cooled screw and the lock hopper of slag. The fly ash captured by the primary cyclone separator and the secondary cyclone separator was also charged by the lock hopper of fly ash. Five temperature probes (dense bed: 3, freeboard: 2) were placed along the height of gasifier. The other probes of temperature, pressure, differential pressure and flow rate were placed along the gasifier, the pipes of fuel gas, preheated air and steam. The data including 20 temperature signals, 15 pressure signals, 6 differential pressure signals, 7 flow rate signals and 2 rotational speed signals were collected by the data acquisition system.

Materials

Xuzhou bituminous coal was used as feedstock

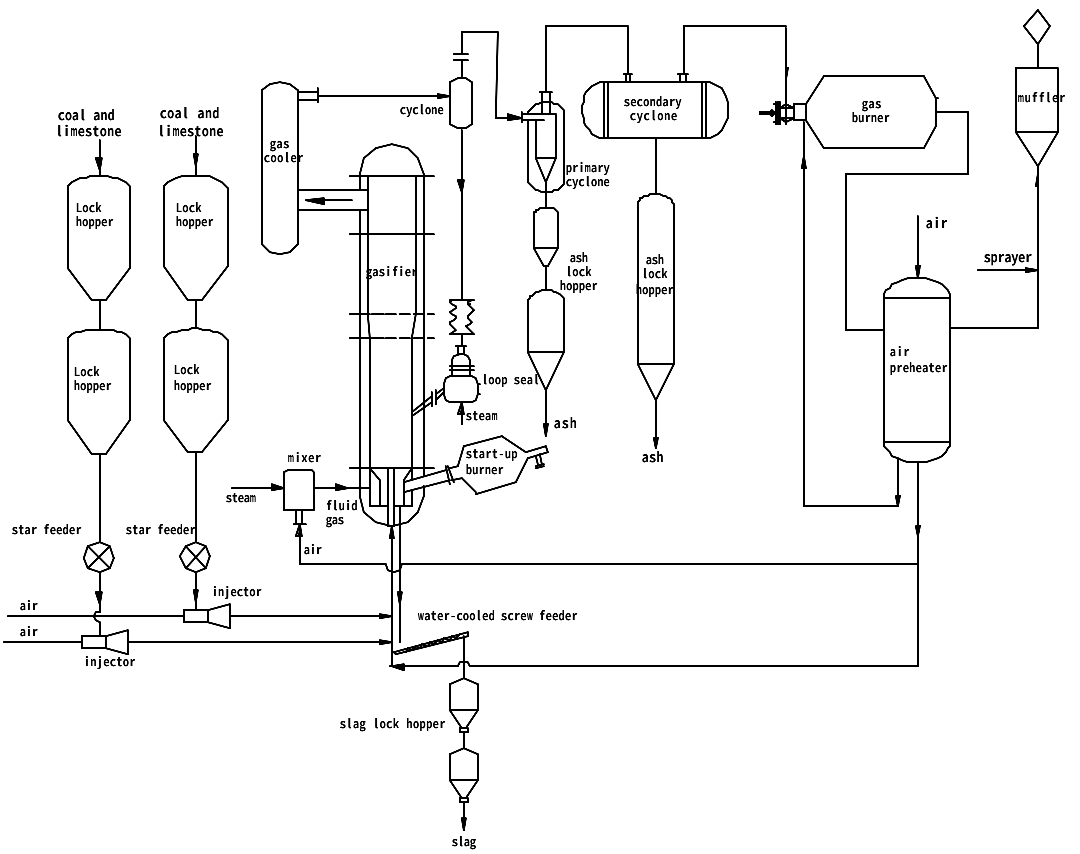

Fig. 1. A schematic diagram of the test facility.

Table 1. The proximate and ultimate analysis of Xuzhou bituminous coal (as received basis)

Proximate analysis:					
M	FC	V	A	HHV	LHV
3 %	45.61%	24.5 %	26.89 %	23.17 MJ/kg	22.35 MJ/kg
Ultimate analysis:					
C	H	O	N	S	A
57.34%	3.62 %	7.51 %	1.05 %	0.59 %	26.89 %

Table 2. The composition of bed material

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	St	Ignition loss
66.25	23.23	5.44	075	0.94	1.52	0.42	0.03	0.46

in the gasification experiments of this study and its proximate and ultimate analysis is shown in Table 1. The range of coal particles size was 0-5 mm. The coal particle size distribution of No.1 and No.3 were different from No.2. The average coal particle size used in No.1 and No.3 was 1.95 mm while that of No.2 was 1.56 mm. The slag discharged from a coal-fired fluidized bed boiler was used as bed material in the start-up of gasification experiments whose composition is shown in Table 2 and its particle size was 0-6 mm.

Test procedure

The start-up period was necessary to preheat the bed material by the flue gas produced from the start-up combustor up to the required temperature before commencement of coal feeding. When the bed temperature reached 450°C, coal was added into the fluidized bed gasifier, and the bed temperature would increase from 450°C to 900°C in 10-15 minutes. The pressure of gasifier increased to 0.5 MPa after the combustion stabilized. The bed was operated at this condition for an hour to ensure that everything for gasification was ready. When the experimental conditions met the demand of coal gasification, the operation state would rapidly change from combustion to gasification by means of adding steam, increasing coal feed rate and reducing air flow rate. The real-time distribution curve of bed temperature in gasifier during the whole test is shown in Fig. 2.

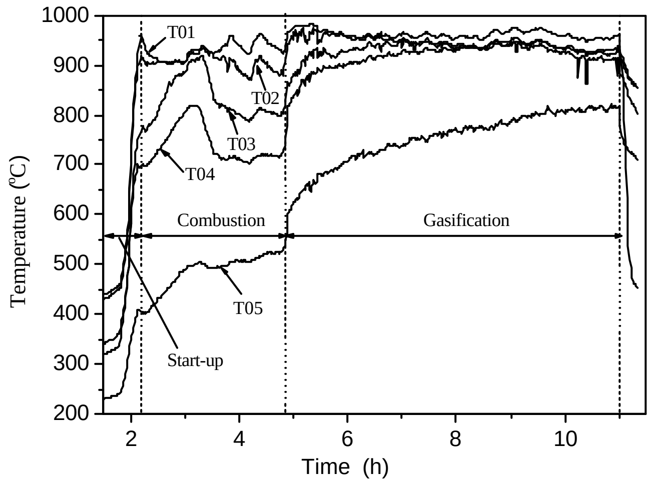

Fig. 2. The real-time distribution curve of bed temperature in gasifier

Method of Analysis

The flow rate of air was determined by an orifice flowmeter and the flow rate of steam was measured by a non-contact mass flowmeter. The correlation computation of flow rate under different temperature and pressure were accomplished by a computer. The fuel gas sampled from the downstream of primary cyclone and secondary cyclone, and the solid samples, such as slag and fly ash, were sent to analyze together. The composition of fuel gas was analyzed by a gas chromatography (Shangfen GC1102). Chromatography calibration was done with standard gas and the standard deviation curve of the typical component was plotted. The carbon contents in slag and fly ash were analyzed according to the correlative state standard, respectively.

Methods of Data Processing

High heating value (HHV) and low heating value (LHV) of fuel gas are defined as following:

$$HHV=(X_{CO}\times 3018+X_{H2}\times 3052+X_{CH4}\times 9500)\times 0.01\times 4.1868\ (kJ/Nm^3) \quad (1)$$

$$LHV=(X_{CO}\times 3018+X_{H2}\times 2581+X_{CH4}\times 8558)\times 0.01\times 4.1868\ (kJ/Nm^3) \quad (2)$$

Where, X_{CO}, X_{H2}, X_{CH4} is the volumetric percentage of CO, H_2, CH_4 in fuel gas, respectively.

The dry gas yield, Y, is figured out from the material balance of nitrogen:

$$Y = \frac{Q_a \times 79\%}{W_C X_{N2}\%} \tag{3}$$

where, Q_a is the flow rate of air (Nm^3/h), W_c is coal feed rate (kg/h), X_{N2} is the volumetric percentage of N_2 in fuel gas.

The carbon conversion is calculated by,

$$x_C = \frac{Y[CO\% + CO_2\% + CH_4\% + 2(C_2H_4\% + C_2H_6\% + C_2H_2\%)] \times 12}{22.4 \times C\%} \times 100\% \tag{4}$$

where, Y is the dry gas yield, C% is the mass percentage of carbon in coal ultimate analysis, the other are the volumetric percentage of fuel gas compositions.

RESULTS AND DISCUSSIONS

Three experiments were performed to study the gasification behavior in a pressurized spout-fluid bed coal partial gasification after the success of system debug. The aim of No.1 and No.2, whose effective stable gasification times were three hours, was to observe the influence of bed temperature on coal gasification. No.3 was a long-time-run test to investigate the reliability, stability and security of gasification system. Two experiments with different work conditions were carried out by the variation of steam flow rate. The whole duration of coal gasification was 12 hours and the effective stable gasification time was 6.5 hours. The optimal carbon conversion of partial coal gasification was about 70% according to the optimal calculation of 2G PFBC [7]. The carbon conversion was kept nearly 70% in our experiments. The main results of No.1, No.2 and No.3 are shown in Table 3.

The real-time distribution curve of bed temperature (T01-T05) in gasifier for No.3 is shown in Fig. 2. The distances of T01-T04 to spout nozzle are 460 mm, 860 mm, 2060 mm and 5260 mm, respectively. T05 locates in the outlet of gasifier. The inserted depth from the wall to the thermal couple is 160 mm.

It can be seen that the fluidizing bed height was about 4.3 m due to the static bed height of 3.6 m in No.3. The temperature of T01-T04 was nearly uniform and the maximum deviation of T01-T04 was only 30 ^oC, which indicated that there was a good fluidization in bed. Since the distribution of bed temperature was uniform in dense phase zone, the high quality fuel gas could be obtained. The main difference of temperature concentrated between T01 and T02 at the bottom of gasifier. The temperature difference was mainly arisen from the inherent character of spout-fluid bed gasification. Once air was introduced into bed via the spout-pipe and the air distributor, coal combusted rapidly at the bottom of the spout-fluid bed and oxygen of air was fast used up. The large amounts of heat were released and a combustion section formed at the bottom of gasifier. The zone above combustion section shifted into reducing zone due to the short of oxygen. Although the mixture in fluidized bed was very violence, the temperature difference between oxidizing zone and reducing zone still existed and became more clear with the progress of gasification reaction, because coal combustion belong to the exothermal reaction while coal gasification belong to the endothermic reaction.

Table 3. Experimental results of pilot-scale coal gasification

Item	Units	NO.1	NO.2	NO.3	
				Run 1	Run 2
Operation pressure	MPa	0.5	0.5	0.5	0.5
Bed temperature	^oC	950	980	960	950
Coal feed rate	kg/h	316.8	330	330	320
Steam flow rate	kg/h	100	100	105	143
Steam pressure	MPa	0.8	0.8	0.8	0.8
Steam temperature	^oC	350	350	270	270
Total air flow rate	Nm^3/h	548	576	567	567
Fluidized air flow rate	Nm^3/h	198	203	163	163
Air temperature	^oC	290	300	270	270
Air pressure	MPa	0.60	0.63	0.63	0.63
Static bed height	m	2.1	2.7	3.6	3.6
Gas composition					
H_2	%	14.36	15.9	15.01	16.54
CO	%	10.55	11.55	11.51	11.68
CO_2	%	13.93	13.46	12.72	12.81
CH_4	%	2.51	1.75	2.7	2.91
N_2	%	57.55	56.84	57.01	55.26
HHV of gas	MJ/Nm^3	4.16	4.18	4.44	4.74
Carbon conversion	%	65.8	67.2	68.4	70.3
Gas yield	Nm^3/kg coal	2.44	2.53	2.51	2.6

The effect of bed temperature on the gasification reaction is the most important, because the gasification reaction in fluidized bed is controlled by the chemical reaction rate, which is directly correlative with bed temperature. At the fixed pressure, air/coal ratio and steam/coal ratio, Table 3 shows the main difference of operation parameters was bed temperature between No.1 and No.2. The bed temperature of No.1 and No.2 were 950 ^oC and 980 ^oC, respectively. Hence, it can be concluded that the difference of experimental results between No.1 and No.2 was arose by bed temperature. The experimental results indicated that the concentration of hydrogen and carbon monoxide in fuel gas increased from 14.63% to 15.9% and from 10.55% to 11.55% respectively while the concentration of methane and carbon dioxide in fuel gas decreased from 2.51% to 1.75% and from 13.93% to 13.46% respectively when the bed temperature increased from 950 ^oC to 980 ^oC under the equilibrium state. An increase of bed temperature accelerated the reaction rate of main heterogeneous gasification reaction in dense phase zone, such as the water-gas reaction between char and steam, the Boudouard reaction between char and carbon dioxide, etc [8]. The decrease of methane was due to volatile released from coal and the secondary reaction mechanism. The sources of methane in fuel gas from pressurized fluidized bed gasifier maybe include coal carbonization, gas-solid methanation reaction and gas-gas methanation reaction. Pang jin et al. [9] have found that the content of methane from the gasification of metallurgical coke and char in fluidized bed was lower and the methane yield produced from gasification reaction was few without catalyst. So volatile of coal was the main contributor of methane in outlet fuel gas from the fluidized bed gasifier. For the same coal, the most notable influencing factor on the concentration of methane in fuel gas was temperature. The concentration of methane decreased sharply due to the secondary cracking of methane with a rise of bed temperature. There was not an apparent effect of bed temperature on the equilibrium heating value of fuel gas. The equilibrium heating value of fuel gas of No.1 and No.2 were all about 4.2 MJ/Nm^3. An increase of bed temperature would quicken the reaction rate of char, shorten the gasification time, and promote the carbon conversion. Thus the carbon conversion increased from 65.8% of No.1 to 67.2% of No.2. More fine particles of coal used in No.2 led to higher fly ash yield and higher carbon content in fly ash than in slag, which would weaken the effect of bed temperature in a certain extent and make the effect of bed temperature on carbon conversion less than the other experiments. In addition, the gas yield increased from 2.44 Nm^3/(kg coal) to 2.53 Nm^3/(kg coal) with an increase of bed temperature. The reason may be the reaction of char and gasification medium was enhanced by an increase of bed temperature and the secondary cracking of methane.

The deep-bed-height gasification technology was applied in No.3. Its static bed height was 3.6 m, which was 1.7 times of that of No.1. With the increase of static bed height, the residence time of gas become longer in high temperature zone, and the concentrations of gasifying products (CO, H_2, etc.) further tended to their chemical equilibrium concentration. Compared the composition of Run 1 of No.3 with that of No.1, the concentration of carbon monoxide, hydrogen and methane increased from 10.55%, 14.36% and 2.51% to 11.51%, 15.10% and 2.70%, respectively, while the heating value of fuel gas increased from 4.16 MJ/Nm^3 to 4.44 MJ/Nm^3. The experimental heating value (4.44 MJ/Nm^3) was only lower 12% than the calculated heating value (5.06 MJ/Nm^3), which indicated that the gasification reaction tended to the chemical equilibrium. At the same time, carbon conversion and gas yield increased when the gasification reaction tended to the chemical equilibrium under the deep-bed-height gasification of coal. However, the overmany increase of bed height could make bad fluidization (such as slugging) in the bed. Under higher pressure, the height/diameter ratio of 8-10 of fluidized bed could ensure the residence time of gas or solid in main reaction zone and avoid slugging in bed.

At the fixed coal feed rate, air flow rate and other operation parameters, the concentration of hydrogen increased apparently from 15.01% to 16.54% when the steam flow rate increased from 105 kg/h (No.3 Run 1) to 143 kg/h (No.3 Run 2). At the same time, the concentration of carbon monoxide and methane increased slightly, while the concentration of carbon dioxide were almost constant, and the heating value of fuel gas increased. With an increase of steam, the gas-solid water–gas reaction and the homogeneous water-gas shift reaction went forward to the positive reaction, which would lead to the rise of hydrogen and carbon monoxide. However, the water-gas shift reaction could decrease the concentration of carbon monoxide. Xiao rui et al. [10] have studied the effects of steam/coal ratio on the composition and heating value of fuel gas and found there was an optimal steam/coal ratio during coal gasification. An increase of steam flow rate led to the decrease of steam cracking. Many undecomposed steam would take a large amount of heat from the gasifier and reduce the bed temperature, which was unfavorable to gasification reaction. It was also proved in this study.

Table 4 shows the comparisons of the experimental parameters and results of pilot-scale facilities of 2G PFBC between this experiment and the others in the world. It can be found that all construction forms were chosen as the spout /jet-fluidized bed with a center jetting air, except Japanese PDU. The reason may be that the percentage of volatile matter dominates in fuel gas from coal partial gasification, and the high temperature of center jetting zone favors the fast volatilization and secondary pyrolysis of volatile matters, which makes the lower content of high molecular tar in fuel gas. In view of coal feed rate and facility scale, the coal feed rate and facility scale of SEU, U.K. CRE and Japanese PDU were similar, while the coal feed rate of U.S. PSDF is 2.2 t/d. The others were smaller than above. At the same time, the deep-bed-height gasification technology was applied by many test facilities, even the lowest fluidizing bed height was 2.0 m (namely the bed height/bed internal diameter was 4.), while the fluidizing bed height of SEU and Japanese PDU reached 4-5m. The high carbon conversion was not the main pursuing object of 2G PFB gasifier, because the char would combust in a CFB/PFB combustor and produce steam without co-firing. The carbon conversion was 70-80% except Shanxi ICC and Beijing ICC. The HHV of fuel gas of American PSDF, SEU and Shanxi ICC were higher while that of U.K. CRE was lower.

CONCLUSIONS

The design of subsystems in the Second-Generation PFB Pilot-Scale Gasifier system was reasonable. The whole system can operate together successfully. The operating mode and the typical work conditions were validated in the tests, which can be used for reference of the large-scale industrial experiments in the future.

The work conditions of partial gasifier are shown as following: the carbon conservation was 70%, the pressure was 0.5 MPa and the bed temperature was 950-980^{o}C. The pressure, bed temperature, carbon content of ash and slag, and the heating value and composition of fuel gas were all stable in the experiment. The variation range of bed temperature was only ± 15^{o}C and the carbon conversion was 65-72%. The measured heating value (4.52-4.74 MJ/Nm^3) of fuel gas was 6-12% lower than the calculated heating value (5.06 MJ/Nm^3), higher than those of same pilot-scale coal gasifier (The HHV of fuel gas of U.K. CRE was 3.7-3.9 MJ/Nm^3 while the LHV of fuel gas of Japanese PDU was 3.3-4.02 MJ/Nm^3), and close to the HHV (4.85 MJ/Nm^3) of fuel gas of American PSDF.

The deep-bed-height gasification technology was applied in No.3. Its fluidizing bed height was about 4.3m (static bed height was 3.6m) and height/diameter ratio reached 9.5. The results show that the experimental heating value of fuel gas approached to the calculated heating value (6%-12% lower than the calculated heating value under equilibrium state), carbon conversion was higher apparently than that in shallow-bed-height gasification, and the operating temperature was nearly uniform in the whole spout-fluid bed. The maximum deviation of bed temperature was only 30^{o}C in the range of 0.86m and 5.26m above the spouting nozzle.

The heating value of coal-char produced from coal partial gasification under the gasification condition (carbon conversion was 70%), including slag and fly ash discharged from gasifier, was about 14.6 MJ/kg. This coal-char could be used as the fuel for boiler and met the combustion mode of a CFB or PFB combustor. The carbon content of fly ash in PFBC was lower than 2% and the combustion efficiency was larger than 99%.

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Table 4. Comparison of experimental results of pilot-scale facilities of 2G PFBC in the world

Item		Units	SEU 2MWth	British CRE	American PSDF	American FWDC	British CTDD	Japanese PDU	Shanxi ICC	Beijing ICC
Types of partial gasifier		–	Spout-fluid bed	Spout-fluid bed	Spouted bed	Jet-fluid bed	Jet-fluid bed	Bubble-fluid bed	Jet-fluid bed	Jet-fluid bed
Size	Internal diameter	mm	F450	F500	F1000	F250	F300	F570	F200	F300
	Overall height	m	10	–	18	10	4 (dense phase zone)	9	4.7	5.5
Parameter	Coals	–	Xuzhou bituminous coal	Baddesley bituminous coal	bituminous coal	Pittsburg#8, Illinois#6	Eight coals in U.K., U.S., Australia, etc.	Two bituminous coals in Australia	Fugu coal	Five coals and chars in Shenmu, Datong
	Coal HHV	MJ/kg	23.17	33.2	–	–	–	–	27.35	24.36-28.26
	Bed pressure	MPa	0.5	0.1	1.0	0.8-1.6	1.3	1.9	0.6-1.53	0.6-1.0
	Bed temperature	℃	950-980	950-1020	870-980	816-982	970(average)	990-1020	880-980	970-1000
	Coal feed rate	kg/h	320-350	424-490	2180	82-238	216-246	515-550	60-168	85-200
	Air flow rate	Nm^3/h	508-534	937-842	2815	197-323	492-540	–	129-291	282-447
	Air/coal ratio	–	1.96-2.08	2.22-2.86	1.29	0.15-0.37	2.2-2.44	–	2.7-3.4	2.3-3.5
	Steam/coal ratio	–	0.31-0.44	0.15	–	0-0.4	0.2-0.53	0.2	0.57-1.0	0.3-0.76
	Fluidizing bed height	m	2.5-4.3	2.0	–	–	–	4.9-5.8	–	–
	Fluidizing velocity	m	1.3	1.6-2.0	1.0	1.0-3.3 (CFB)		–	–	–
Result	Gas yield	Nm^3/kg	2.44-2.61 (dry)	–	–	–	–	–	3.28-3.53	2.5-6.3
	Carbon conversion	%	69-72	70-79	65-75	30-80	71-79	72-75	70-85	63-94
	Gas HHV	MJ/Nm^3	4.52-5.0	3.7-3.9	4.85	0.2-0.5 HHV_{gas}/HHV_{coal}	3.9-4.6	3.3-4.02(LHV)	4.8-5.0	2.8-4.5 (LHV)