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循环流化床煤气化试验研究

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EXPERIMENTAL STUDY ON COAL GASIFICATION IN A CIRCULATING FLUIDIZED BED

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ABSTRACT: Experiment results on gasification of a bituminous coal in a pilot scale circulating fluidized bed at atmospheric pressure and different operation conditions, rates of coal feed from 5.4 to 8.14kg/h, ratios of steam/coal from 0.19 to 0.7kg/kg and ratios of air/coal from 2.8 to 3.67kg/kg, are reported. The effect of operation conditions on gas compositions, calorific values, carbon conversions and gasification efficiencies are analyzed. At present stage, the maximum calorific value of product gas was 3.84MJ/Nm^3 and the highest coal conversion efficiency was 73.7%. Much carbon was lost in fly ash after the cyclone due to the short of the lift, the low gasification temperatures and the low separation efficiency of the cyclone for fine particles. Gasification temperature must be limited to 930℃ for Shenhua coal to avoid slagging.

KEY WORDS: Thermal power engineering; Coal gasification; Circulating fluidized bed; Experimental study

摘要：在常压循环流化床中试装置上进行了神华煤的气化试验，试验条件：加煤速率 5.4~8.14kg/h、蒸汽煤比 0.19~0.7kg/kg、空气煤比 2.8~3.67kg/kg，分析了试验条件对煤气组成、热值、碳转化率和煤气效率的影响。在该试验阶段获得的煤气的最高热值为 3.84MJ/Nm^3，最高碳转化率为 73.6%。由于提升管的高度很小、气化温度较低以及旋风炉对细颗粒分离效率不高，导致损失于飞灰中碳较多。试验结果表明对神华煤而言，气化温度应低于 930℃以避免结渣。

关键词：热能动力工程；煤气化；循环流化床；试验

1 INTRODUCTION

Coal is the most important energy sources in China. Coal gasification is a clean coal technology that presents good prospects for coal use, mainly for producing electricity with a high coal conversion efficiency and low environmental impact[1-2]. Among the coal gasification processes, the fluidized bed process is preferred because of its many inherent advantages, such as excellent gas-solid contact, enhanced heat transfer and reaction rate and its capability to handle a wide variety of coals[3-4]. The circulating fluidized bed (CFB) gasifier operates in a mode between the classical bubbling bed and the pneumatic transport reactor, and the slip velocity between solids and gas is the highest[5]. It possesses better mixing of gas and solid, higher production capacity as well as easier scaling up than a bubbling bed. Since the beginning of 1980s, CFB gasification has gained increasing interest and several CFB gasifiers for wood and bark have been built by Ahlström and Lurgi[6]. Gasification tests of coal and other fuels were conducted for a total of more than 6000 hours by Lurgi[7]. Since 2001, a total of 22 test points with 5 coals (sub-bituminous or bituminous) and petroleum coke using air or oxygen enriched air were completed by F-W[8-12] for the Vision 21 program. Fang[13] investigated gasification of coals and chars with CO2 and CO2/O2 mixture in a CFB gasifier with electric heater and made a mathematical model. Shadle[14] studied coal gasification in a transport reactor. However, published papers on CFB

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gasification are insufficient in respect of experiment data and analysis.

A pilot scale CFB gasifier was built in 2002 and some preliminary experiments were made[15]. The purpose of the program is to make gas with CFB gasifiers for gas turbines to produce electricity power. To further study performance characteristics of the CFB gasifier and to optimize operating conditions over 70 cases have been investigated in the last two years and described here in detail.

2 EXPERIMENTS

2.1 Characteristics of Coal

Experiments were made with a bituminous, Shenhua coal. The proximate and ultimate analysis results are given in Table 1, the ash compositions in Table 2 and the size distribution in Fig.1. Coal particles are smaller than 3 mm, with 50% cut size about 0.72 mm.

表 1 神华煤质分析

Tab. 1 Analysis of Shenhua coal

Parameters Analysis		Value
Ultimate analysis/w% (air dried basis)	Carbon	68.84
	Hydrogen	3.56
	Nitrogen	0.71
	Sulfur	0.40
	Oxygen	11.08
Proximate analysis (air dried basis)	Volatile/w%	27.60
	Volatile/w% (dry ash free basis)	32.63
	Fixed carbon/w%	56.99
	Moisture/w%	6.88
	Ash/w%	8.53
	LHV /(MJ/kg)(as received basis)	25.87
Ash fusibility	Deformation temperature (DT)/℃	1080
	Softening temperature (ST)/℃	1190

表 2 神华煤灰成分

Tab. 2 Ash composition of Shenhua coal

单位：%

Ash Compositions	Value
SiO_2	25.32
Fe_2O_3	22.11
CaO	26.64
P_2O_5	0.02
MgO	0.95
TiO_2	0.69
Al_2O_3	10.77
Na_2O	1.75
K_2O	0.49
SO_3	9.06

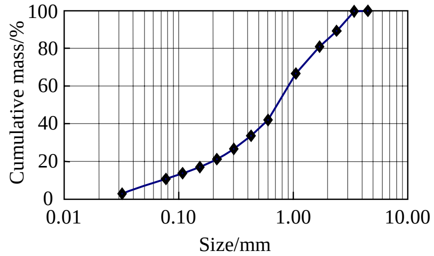
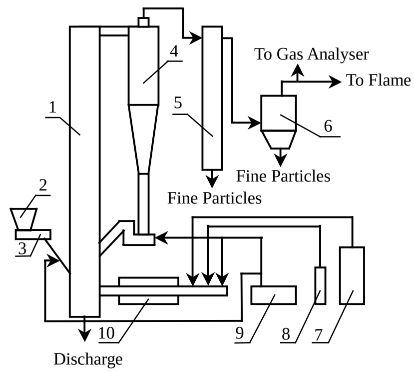


图 1 神华煤粒度分布

Fig. 1 Size distribution of Shenhua coal

2.2 The CFB Gasifier

The schematic diagram of the CFB gasifier is presented in Fig. 2. It consists of a lift tube with an inner diameter of 100 mm and a height of 3000 mm, a cyclone, a standpipe and a U-valve. The CFB gasifier is made of high temperature alloy covered with isolating matter on the outside.



Note: 1-lift, 2-coal silo, 3-screw feeder, 4-cyclone, 5-water-tube cooler, 6-bag filter, 7-electrical boiler, 8-LPG tank, 9-air compressor, 10-electrical pre-heater.

图 2 循环流化床煤气化试验台示意图

Fig. 2 Schematic diagram of the CFB gasifier

Coal is fed into the bottom of the lift with a screw feeder. Gasification agents (preheated air and steam) are added to the lift through an air distributor on the bottom. Air is used to fluidize the particles in the U-valve. After leaving the cyclone, gas is cooled down in a water-tube cooler and fly ash is collected with a bag filter. Gas is sampled for an online analyzer (ICK-MAIHAK S710) to analyze CO、CO_2、H_2 and CH_4.

2.3 Experiment Procedure

Quartz sand smaller than 1 mm and in 3 kilograms was added into the lift as bed material and then heated up with combustion of liquefied petroleum gas. Coal was gradually fed into the lift and gas was withdrawn when the temperature of the bottom bed of the lift was over 400℃. Steam was added when the bed temperature about 800℃. A case test lasted about one hour, and ash samples at the bottoms of the water-tube cooler and the bag filter were taken in the end. Then the test conditions were adjusted to the other cases.

2.4 Experiment Conditions and Results

Some typical experiment results and the operation conditions are totally shown in Table 3.

表 3 典型试验条件及结果

Tab. 3 Typical experiment conditions and results

No.	F_c/(kg/h)	F_a/F_c/(kg/kg)	F_s/F_c/(kg/kg)	$\varphi(CO_2)$/%	φ(CO)/%	$\varphi(H_2)$/%	$\varphi(CH_4)$/%	T_b/℃	Q_g/(MJ/Nm^3)	C_{conv}/%	E/%
1	5.4	2.79	0.51	14.90	9.14	9.75	0.83	795	2.73	55.08	29.04
2	5.4	3.01	0.51	13.21	12.50	11.28	0.80	823	3.34	66.64	40.26
3	5.4	3.23	0.51	12.54	13.46	10.85	0.70	849	3.36	71.75	43.38
4	5.4	3.43	0.51	12.46	13.26	9.79	0.63	878	3.18	73.91	42.77
5	5.4	3.67	0.51	12.74	12.24	7.47	0.51	941	2.70	72.56	36.93
6	5.4	2.79	0.70	14.70	10.35	12.68	0.89	794	3.28	61.26	37.19
7	5.4	3.01	0.70	14.19	11.10	12.25	0.79	814	3.28	66.10	39.89
8	5.4	3.23	0.70	13.97	11.15	11.58	0.74	839	3.18	69.33	40.94
9	5.4	3.43	0.70	13.67	11.10	10.12	0.66	878	2.95	70.41	39.29
10	5.4	3.67	0.70	13.67	10.53	8.06	0.51	928	2.56	69.87	34.77
11	5.4	2.79	0.21	11.99	13.40	10.31	0.87	812	3.35	60.19	36.90
12	5.4	3.01	0.21	10.86	14.95	9.99	0.76	844	3.46	65.57	41.05
13	5.4	3.23	0.21	10.66	14.91	9.39	0.71	873	3.36	68.53	42.10
14	5.4	3.43	0.21	10.60	14.61	8.33	0.63	904	3.16	69.87	40.99
15	5.4	3.67	0.21	10.89	13.83	7.16	0.56	933	2.88	71.49	39.15
16	6.4	2.80	0.19	13.14	13.56	11.02	0.87	821	3.47	65.50	39.54
17	6.4	3.00	0.19	12.00	15.23	10.73	0.75	849	3.59	71.40	43.98
18	6.4	3.22	0.19	11.95	15.00	9.64	0.69	885	3.40	73.67	43.48
19	8.14	2.43	0.25	11.48	13.88	11.28	0.96	790	3.57	53.42	34.83
20	8.14	2.67	0.25	9.97	16.36	11.39	0.80	822	3.84	61.69	41.56
21	8.14	2.90	0.25	10.05	15.95	10.59	0.72	857	3.65	64.67	42.43
22	8.14	3.10	0.25	9.90	15.92	9.26	0.62	903	3.44	66.27	41.40

Note: F_c, coal feed rate; F_a/F_c, air/coal ratio; F_s/F_c, steam/coal ratio; T_b, bed temperature, $T_b=(T_1+T_3)/2$, where T_1,T_3 are the temperatures at the top and the bottom of the lift, respectively; Q_g, low heating value (LHV) of dry product gas; C_{conv}, carbon conversion, $C_{conv}=v_g[\varphi(CO)+\varphi(CO_2)+\varphi(CH_4)]/(MC_{ar})$, where M is the coal feed rate, v_g the flow rate of dry product gas and C_{ar} the carbon content of the coal as received basis; E, gasification efficiency, $E=(v_gQ_g)/(MQ_{coal})$, where Q_{coal} is LHV of the coal.

3 DISCUSSION

3.1 Temperature

Higher temperatures lead to higher coal conversion, higher coal throughput[16]. But in a CFB gasifier, the gasification temperatures must be limited to avoid coking and slagging and it is a big disadvantage. To Shenhua coal, the highest bed temperature was only 930℃, 260℃ lower than its softening point. Peng[17] operated a pressurized bubbling bed gasifier with the same coal at a furnace temperature about 270℃ lower than its softening point and Chatterjee[3] did the same to a similar bituminous coal.

3.2 Effect of F_a/F_c on CFB Gasification

It is clear shown in Fig. 3 that the bed temperatures increase linearly with the increasing of the air/coal ratios. To gas products and gasification efficiencies, there are the most suitable air/coal ratios

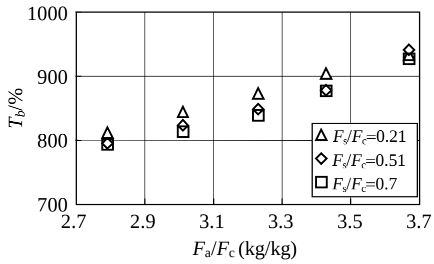


图 3 床温与空气/煤比的关系(F_c=5.4kg/h)

Fig. 3 Bed temperature versus F_a/F_c (F_c=5.4kg/h)

between 3.2 to 3.4 kg/kg shown in Fig. 4 and Fig. 5, about 0.7 larger than that in Ocampo's report[18]. But the problem is that the two best points are at the lower bed temperatures, between 850℃ to 870℃ in Fig. 3. The benefit of high bed temperatures is not presented in gas products, gasification efficiencies and even carbon conversions (Fig.6). The highest carbon conversion efficiency is only 74%. It means that much carbon is residual in fly ash after the cyclone due to the short of the lift, low gasification temperatures and

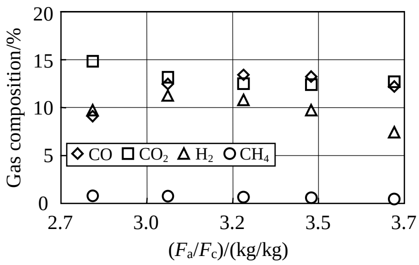


图4 煤气组成与空气/煤比的关系(F_s/F_c=0.51, F_c=5.4kg/h)

Fig. 4 Gas composition versus F_a/F_c (F_s/F_c=0.51, F_c=5.4kg/h)

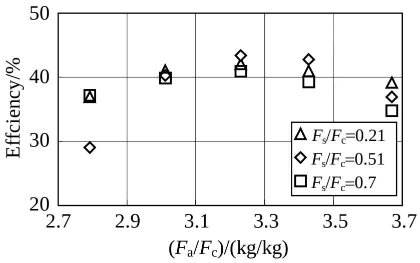


图5 气化效率与空气/煤比的关系(F_c=5.4kg/h)

Fig. 5 Gasification efficiency versus F_a/F_c (F_c=5.4kg/h)

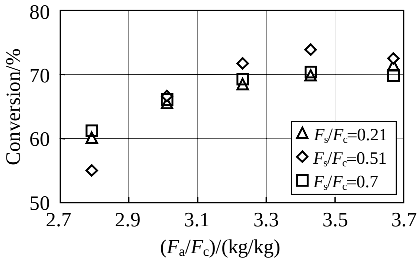


图6 碳转化率与空气/煤比的关系(F_c=5.4kg/h)

Fig. 6 Carbon conversion efficiency versus F_a/F_c (F_c=5.4kg/h)

the low efficiency of the cyclone for fine particles.

3.3 Effect of F_s/F_c on CFB Gasification

With mixing steam to air, the concentrations of H_2 increase but CO decrease, shown in Fig. 7. It is shown in Fig. 8 and Fig. 9 that the steam/coal ratio of 0.5 kg/kg is the best to carbon conversions and gasification efficiencies, but the low heating values of dry product gas and the bed temperatures are

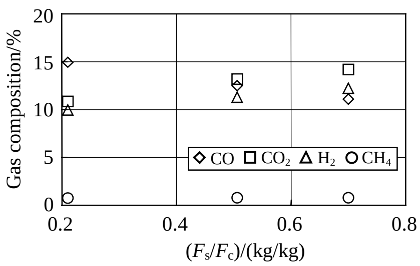


图7 煤气组成与蒸汽/煤比的关系(F_a/F_c=3，F_c=5.4kg/h)

Fig. 7 Gas Composition versus F_s/F_c (F_a/F_c =3, F_c=5.4kg/h).

decreased with the increasing of steam shown in Fig. 10 and Fig. 11, the tendencies are common.

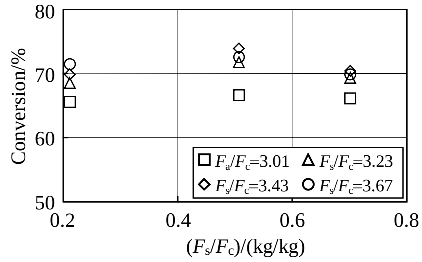


图8 碳转化率与蒸汽/煤比的关系（F_c=5.4kg/h）

Fig. 8 Carbon conversion efficiency versus F_s/F_c (F_c=5.4kg/h)

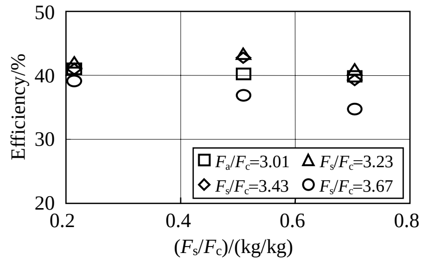


图9 气化效率与蒸汽/煤比的关系（F_c=5.4kg/h）

Fig. 9 Gasification efficiency versus F_s/F_c (F_c=5.4kg/h)

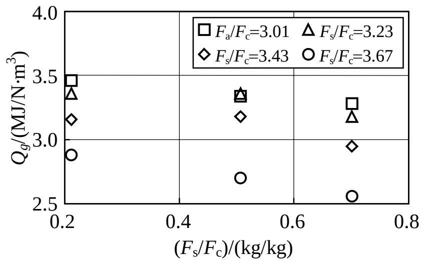


图10 煤气热值与蒸汽/煤比的关系(F_c=5.4kg/h)

Fig. 10 Low heating value versus F_s/F_c (F_c=5.4kg/h)

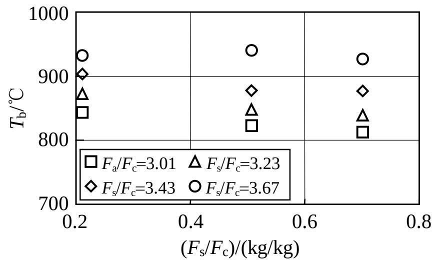


图11 床温与蒸汽/煤比的关系(F_c=5.4kg/h)

Fig. 11 Bed temperature versus F_s/F_c (F_c=5.4kg/h)

3.4 Effect of F_c on CFB Gasification

To increase coal feed rates to 8.14kg/h the highest low heating value of 3.84MJ/Nm^3 is gained at F_a/F_c of 2.67kg/kg, shown in Fig. 12, on the other hand, the carbon conversion efficiency is as low as 61% at the case, in Fig. 13. It is shown in Fig. 13 that carbon conversion efficiency is not modified with the change of the coal feed rate. The low heating value of 3.84MJ/Nm^3 is a little lower than that made by Peng[14] with the same coal and similar conditions in a pressurized bubbling bed model.

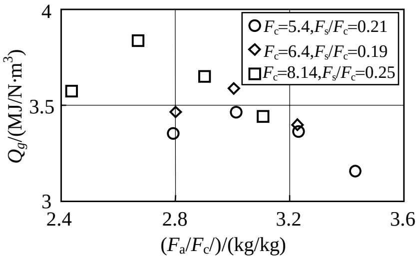


图 12　煤气热值与空气/煤比的关系

Fig. 12　Low heating value versus F_a/F_c

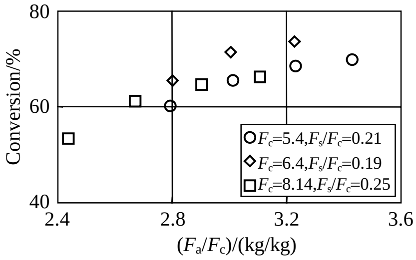


图 13　碳转化率与空气/煤比的关系

Fig. 13　$C_{conv.}$ versus F_a/F_c

4　CONCLUSION

A series experiment of gasification was made with Shenhua coal in a pilot scale CFB gasifier to investigate the effects of air flow, steam flow and coal feed rates on gasification efficiencies, gas composition, low heating value, carbon conversion and bed temperatures.

The bed temperature must be limited to 930℃ for Shenhua coal to avoid slagging. The maximum calorific value of product gas was 3.84MJ/Nm^3 and the highest coal conversion efficiency 73.67% at present stage. Much carbon was lost in fly ash after the cyclone due to the short of the lift, the low gasification temperatures and the low separation efficiency of the cyclone for fine particles.

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