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Partial gasification of coal in a fluidized bed reactor: Comparison of a laboratory and pilot scale reactors

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Abstract−A 0.1 MW_{th} lab-scale and 2 MW_{th} pilot-scale experimental rigs were constructed to demonstrate the technical feasibility of a new process. The aim of the lab-scale study is to optimize coal partial gasification reactions operating conditions, which were applied in the pilot-scale tests. A comparison between the laboratory and pilot scale experimental results is presented in this paper in order to provide valuable information for scaling-up of the PFB coal partial reactor to industrial applications. The results show that trends and phenomena obtained in the laboratory reactor are confirmed in a pilot plant operating at similar conditions. However, many differences are observed in the two reactors. The higher heat loss in the lab-scale reactor is responsible for higher equivalence ratio (ER) and lower gas heating value at the similar reactor temperature. With respect to the pilot-scale reactor, mass transfer limitation between bubbles and emulsion phase may become important. Hence, longer contact time is required to achieve the same conversions as in the lab-scale reactor. This difference is explained by a significant change of the hydrodynamic conditions due to the formation of larger bubbles.

Key words: Partial Gasification, Coal, Gasification Characteristics, Lab-scale Test, Pilot-scale Test

INTRODUCTION

Advanced gas turbine combined cycle technologies have the promise of being able to produce electricity with a high efficiency and low emissions [Beer, 2000]. The Air Blown Gasification Cycle (ABGC) [Minchener et al., 1993] and Advanced Pressurized Fluidized Bed Cycle (APFBC) [Wheeldon et al., 2001] are some of these new generations of cleaner technologies being developed. The new processes partially gasify coal at elevated pressure to produce a coal derived gas and a char residue. The gas can be used to fuel the most advanced gas turbines, while the residual char can also be used to generate electricity by firing boilers that drive the most advanced ultra-supercritical pressure steam turbines. From the coal conversion process point of view, coal gasification is a two-step process. In the first step, pyrolysis, volatile components of coal are released, leaving residual char as by-products. The second step, char conversion, involves the gasification of residual char. Studies show that the kinetic reaction rate usually decreases with coal conversion, because the higher reactivity parts react faster than the residual char since the ash layer thickens causing diffusion resistance to increase during the coal or char conversion process [Tang and Wang, 2000]. Therefore, the unique aspect of the process is that it does not attempt to convert coal in a single step like IGCC. To convert all the coal to syngas in a single step requires extremely high temperature (>1,500 °C) that melts and vaporizes the coal and drives all coal contaminants into the syngas. The new process utilizes a pressurized spout-fluid bed partial gasifier operating at much lower temperature that controls the release of contaminants, and this minimizes the need for expensive, complicated gas heat exchangers and chemical cleanup systems typical of high temperature gasification.

The spout-fluid bed is proposed for a coal partial gasifier because of the strong solids mixing which favors the coal devolatilization process. In addition, this kind of reactor can process caking coals which become sticky when heated through the plastic stage and which present problems in fluidized or moving beds. The high velocity jet at the bottom of the reactor tends to break up any agglomerates that might form within the bed [Watkinson et al., 1983]. Successful commercialization of spout-fluid bed gasifiers is crucially dependent on a proper understanding of the scaling up principles of the reactor. Many valuable experimental and theoretical studies on coal gasification have been carried out in the past several years [Lee et al., 2002, 2006; Zhou et al., 2005; Xiao et al., 2006, 2007; Choi et al., 2006]. However, comparative tests where the same coal has been gasified in a lab-scale and in a pilot-scale spout-fluid bed reactor have not been reported. In the present work, a comparison between lab-scale and pilot-scale gasifier was therefore carried out to determine the coal partial gasification characteristics between the two different scale gasifiers.

EXPERIMENTAL

1. Coal Characteristics and Preparation

The coal used in the lab- and pilot-scale gasification tests is one

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Table 1. Proximate and ultimate analysis of Xuzhou bituminous coal

	Proximate analysis (wt%)				Ultimate analysis (wt%)					$Q_{net.ar}$ (MJ/kg)
	M_{ar}	V_{ar}	A_{ar}	C_{fix}	C_{ar}	H_{ar}	O_{ar}	N_{ar}	S_{ar}	
Xuzhou coal	3.0	24.5	26.9	45.6	57.34	3.62	7.51	1.05	0.59	22.35

Table 2. Xuzhou bituminous coal ash analysis

Ash composition (wt%)									Ash fusion temperature (°C)		
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	S_{total}	others	DT	ST	FT
61.35	25.13	5.44	4.72	0.94	1.52	0.42	0.03	0.45	1150	1310	1420

Table 3. Distribution of particle size of Xuzhou bituminous coal and bed material

Particle size (mm)	Xuzhou coal (wt%)		Bed material (wt%)	
	Lab-scale	Pilot-scale	Lab-scale	Pilot-scale
0-0.6	25.1	19.7	5.5	20.1
0.6-1.0	71.1	9.3	89.7	15.6
1.0-1.5	3.8	8.6	4.8	9.8
1.5-2.0	-	15.3	-	14.1
2.0-2.5	-	12.2	-	8.1
2.5-3.0	-	17.5	-	13.9
3.0-5.0	-	17.4	-	18.4
Mean diameter (mm)	0.68	1.95	0.75	1.85

of the main coal types for power generation plants in China. It is a high ash, high ash melt point, and low sulfur bituminous coal.

The analysis and characterization of the coal samples is presented in Table 1, and the ash elemental analysis is displayed in Table 2. In order to avoid defluidization problems such as slagging and agglomeration, two different coal particle sizes have been used in the lab-scale and pilot-scale tests, respectively. The coal particle size distribution is shown in Table 3. From Table 3, the average size of coal used in lab-scale test is 0.68 mm, much smaller than the size of 1.95 mm employed in pilot-scale test. The bed inert materials used in all the tests are bottom ash from a circulating fluidized bed boiler with an average size of 0.75 mm in the lab-scale study and of 1.85 mm in the pilot-scale study, a particle density of 2.3 g/cm^3, and a bulk density of 1.1 g/cm^3. The bed material size distribution is also shown in Table 3.

2. Laboratory Scale Equipment

Fig. 1 shows a schematic diagram of the lab-scale set-up. The whole system consists of an air/steam providing section, an air/steam pre-heater section, a spout-fluid bed gasifier, coal feeding section, a gas cooling, clean-up, sampling and burning section, and a temperature and pressure control section.

The gasifier is made of a stainless steel (Cr15Ni20) of 80 mm i.d. and of 4.2 m in height, with a 500 mm i.d. pressure vessel outside. The reactor has two individually controlled electric heaters (bed, freeboard) that supply heat for start-up and counter heat loss during operation. Two pressure taps are mounted at the bottom and outlet of the reactor to monitor the fluidization state in the reactor. Seven thermocouples are installed across the reactor, one in wind-box, three in dense bed, two in freeboard, and one in outlet of the reactor. A

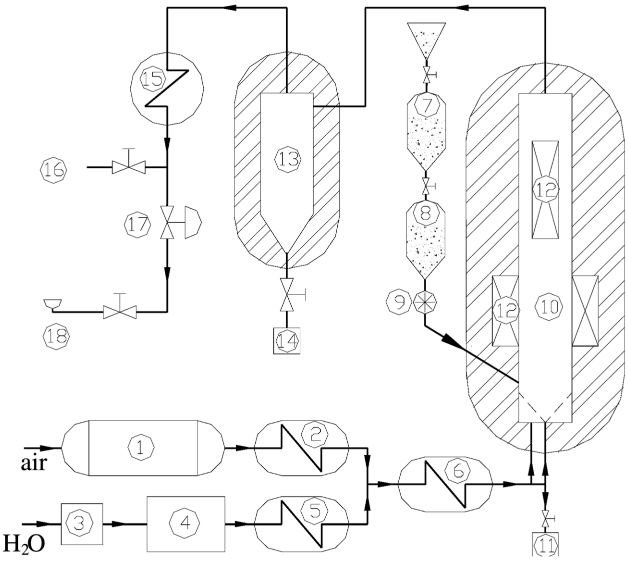

Fig. 1. Schematic of lab-scale pressurized spout-fluid gasifier.

1. Air compressor
2. Low temperature air heater
3. Water tank
4. Boiler
5. Steam superheater
6. High temperature air/ steam heater
7. Swing hopper
8. Feed hopper
9. Star feeder
10. Gasifier
11. Slag hopper
12. Electric heater system
13. Cyclone
14. Ash hopper
15. Gas cooler
16. Gas sampling
17. Control valve
18. Gas combustor

60° conical distributor with 60 holes of 1 mm i.d. perforated uniformly on it is mounted at the bottom of the reactor for better air distribution. A pipe with 10 mm i.d. is used to introduce the spouting air to the reactor. Coal is fed via a variable-speed star feeder. Air from the compressor is preheated by a low-temperature air heater, while steam from a boiler is heated by a superheater. Then the two gases are mixed and heated by a high-temperature heater. The air and steam flow rates are measured by mass flow meters. About half of the gasifying agent is diverted to the spouting nozzle, while the other enters the reactor through the distributor. After the gas leaves the reactor, a small cyclone removes particles in the gas which are collected in an ash hopper. Then the gas is cooled by a water cooler to condense un-decomposed steam. Part of the gas leaving the cooler is sampled by using gas bags for gas offline analysis.

3. Pilot Scale Equipment

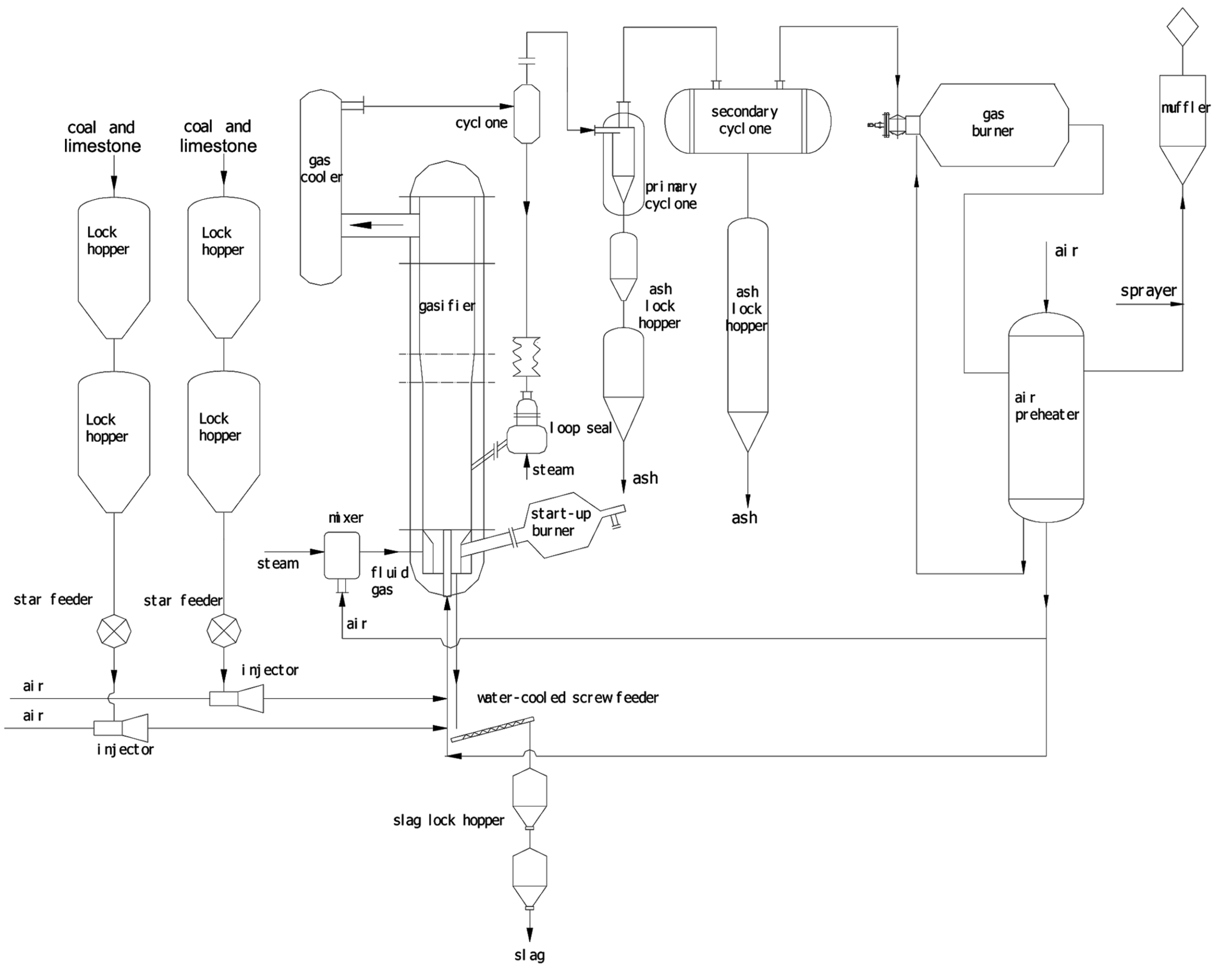

Fig. 2. Schematic of pilot-scale pressurized spout-fluid gasifier.

The pilot scale partial gasifier system, shown in Fig. 2, consists of seven main parts: (1) coal and limestone feeding system; (2) air and steam supply and preheated system; (3) gasifier equipped with a cyclone and a particle recirculation system; (4) gas clean up and gas sampling system; (6) gas combustor equipment; (7) data acquisition system. The gasifier is a refractory-lined reactor with inside diameter of 0.45 m in dense bed, and expands to inside diameter of 0.64 m in freeboard. The total height of the gasifier is 10.5 m. Five temperature probes (from T1 to T5) measure the temperature variations across the gasifier. The probes T1-T3 monitor the temperature at the gasification reaction zone, and the probes T4-T5 monitor the upper zone. The feeding system consists of two lock hoppers by which the feedstock is brought up to process pressure. Via a rotary impeller, the feedstock is conveyed into an injector where it is pneumatically conveyed to the bottom of the gasifier. A variable rotating motor on the base of the calibration curve contols the feedstock feed rate. Limestone was not actually fed during the tests. The gas sampling point is located downstream of the secondary cyclone. The fuel gas is fired in a combustor before venting. A further description can be found elsewhere [Xiao et al., 2005].

4. Methods of Measurement and Data Processing

The gas composition is analyzed on a gas chromatograph (GC-1102, China) to detect H_2, O_2, N_2, CO, CO_2, and CH_4. Chromatograph calibration is done with standard gas, and a standard deviation curve of the typical component is drawn. Argon is used as the carrier gas at a flow rate of 44 mL/min. The temperature of the chromatography column is 80 °C, and the temperature of the thermal conductivity detector (TCD) is 120 °C.

The higher heating value (HHV) and lower heating value (LHV) of the fuel gas on dry basis are calculated from the fuel gas composition. Carbon conversion to dry gas is calculated on carbon evolution (mass flow rate of carbon in fuel gas used divided by the mass flow rate in coal). The nitrogen balance is used to calculate the gas yield on dry basis. Cold gas efficiency is calculated based on the total heating value of fuel gas used divided by the coal heating value. For detail calculating processes see [Xiao et al., 2006].

RESULTS AND DISCUSSIONS

Comparative tests were carried out in two different scale gasifiers. Table 4 presents the configuration and operating conditions of the two reactors. Both the lab-scale and pilot-scale gasifiers employ Xuzhou bituminous coal as a feedstock and a spout-fluid bed as reactor type. The gasification temperature and pressure are similar, with 940 °C, 0.5 MPa in the lab-scale gasifier and 950 °C, 0.5 MPa in the pilot-scale gasifier. Since slugging can easily occur in a small reactor diameter and high operating bed height reactor, a lower static bed height to reactor diameter ratio (H/D) is used in the lab-scale

Table 4. Configuration and operating parameters of the reactors

	Lab-scale gasifier		Pilot-scale gasifier	
	Gasifying agent temperature 300 °C (run 1)	Gasifying agent temperature 700 °C (run 2)	Gasifying agent temperature 310 °C (run 3)	Gasifying agent temperature 270 °C (run 4)
Coal type	Xuzhou coal	Xuzhou coal	Xuzhou coal	Xuzhou coal
Particle size/mm	0.68	0.68	1.95	1.95
Gasifier type	Spout-fluid bed	Spout-fluid bed	Spout-fluid bed	Spout-fluid bed
Reactor diameter/mm	80	80	450	450
Reactor height/mm	4200	4200	10500	10500
Static bed height/mm	300	300	2100	3600
Reaction temperature/°C	940	940	950	950
Reactor pressure/MPa	0.5	0.5	0.5	0.5
Coal feeding rate/kg/h	8.0	8.2	317	320
Equivalence ratio (ER)	0.38	0.34	0.29	0.31
Steam to coal ratio (wt/wt)	0.38	0.42	0.32	0.45
Superficial gas velocity/m/s	0.72	0.64	1.2	1.3

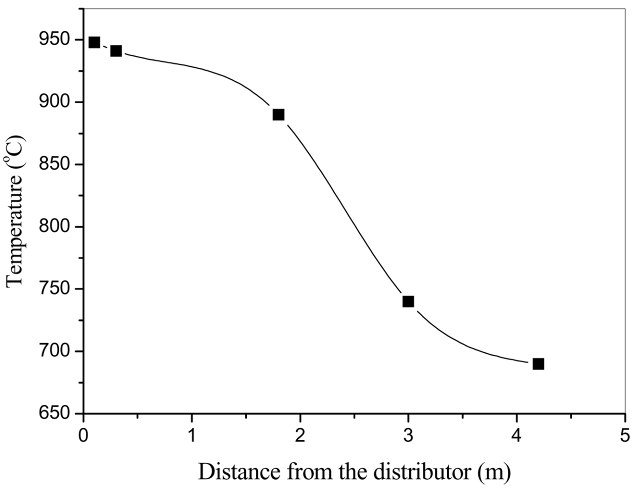

Fig. 3. Axial temperature profile in the lab-scale gasifier.

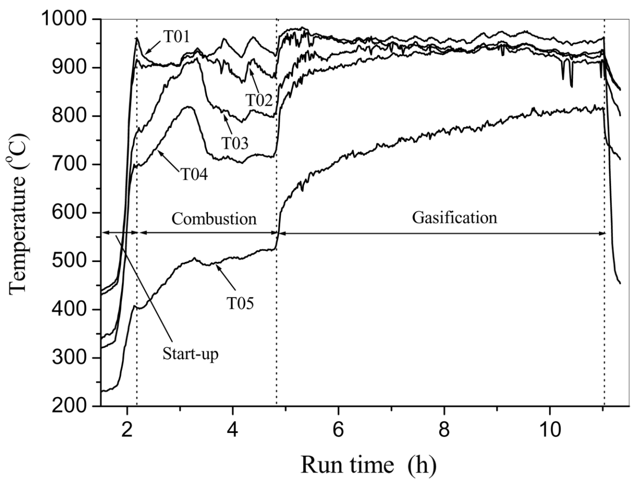

Fig. 4. Axial temperature profile in the pilot-scale gasifier.

reactor. The lower superficial gas velocity is applied in the lab-scale set-up due to the smaller coal particle size and minimum fluidizing velocity thereafter. The major difference of two runs (run 1 and run 2) in lab-scale tests is gasifying agent temperature, 300 °C in run 1 and 700 °C in run 2. The pilot-scale tests (run 3 and run 4) are distinguished in static bed height. Static bed height in run 4 is much higher than that of in run 3.

1. Temperature Profile

The temperature profiles along the gasifier height in the lab- and pilot-scale tests are shown in Fig. 3 and Fig. 4, respectively. From Fig. 3 and Fig. 4, both gasifiers have a uniform temperature distribution in the dense bed due to the good gas/solid mixing. However, the axial temperature drops dramatically from 945 °C in the dense bed to 687 °C in the gasifier exit during the lab-scale test. Whereas, the pilot-scale gasifier shows more uniform axial temperature distribution, and the temperature in the reactor exit is approximately 800 °C under the heat balance state. The reason for this behavior may lie in the relatively large surface-to-volume ratio of the lab-scale gasifier, which leads to higher heat losses. The energy balance of a gasifier can be expressed as below:

Chemical energy of coal+Sensible heat of gasifying agent=Chemical energy of gas+Sensible heat of gas and fly ash+Chemical energy residual char+Heat losses from the wall of a gasifier.

Therefore, heat losses from a gasifier can be determined from the above equation. Heat losses from the lab-scale gasifier vary within 12-15% relative to the coal feed rate, while heat losses from the pilot-scale are only 5-6%. Shadle et al. [2001] concluded from the model that heat losses above 10% would influence the gasifiers' performance. The effect of heat losses on the performance of a gasifier in the present work will be discussed later.

2. Gas Composition

The fuel gas composition and other gasification indicators of the gasifiers are listed in Table 5. Comparing run 1 and run 3, the reaction temperature and gasifying agent temperature are kept almost constant. The combustible compositions (H_2 and CO) in the fuel gas from the pilot-scale run are higher than those of the lab-scale run. Due to more heat loss, a much higher ER is required to keep the reaction temperature in the lab-scale facility. That means more

Table 5. Gasification results of the reactors

	Lab-scale gasifier		Pilot-scale gasifier	
	Gasifying agent temperature 300 (run 1)	Gasifying agent temperature 700 (run 2)	Gasifying agent temperature 310 (run 3)	Gasifying agent temperature 270 (run 4)
Gas composition (vol%)				
H_2/%	10.6	15.2	14.6	16.3
CO/%	10.5	12.2	10.8	11.6
CO_2/%	15.3	13.5	13.1	12.9
CH_4/%	2.3	2.4	2.6	2.9
N_2/%	60.3	55.7	56.0	55.3
Unconverted carbon (wt%)				
Fly ash	32.8	34.5	41.1	36.2
Bottom ash	20.3	19.6	34.2	27.8
Gas heating value/MJ/Nm^3	3.6	4.4	4.23	4.73
Dry gas yield/Nm^3/kg coal	3.1	3.1	2.44	2.6
Carbon conversion/%	78.8	78.2	62.3	68.8
Cold gas efficiency/%	48.1	58.8	46.1	54.9

air is introduced and more combustible things (combustible gas and char) are burnt; it is also the reason for the higher CO_2 concentration in the lab-scale test. The CH_4 content is roughly the same in both gasifiers. Higher hydrocarbons (C_2H_6, etc) and tar were not detected due to perfect solid/gas mixing in the fluidized bed reactors.

If we look at the H_2 and CO contents in Table 5, one interesting thing is that the concentration of H_2 is greater than that of CO at both gasifiers' test runs. The result is very different from a high-temperature winkle (HTW) gasifier operating at a similar temperature. Watkinson et al. [1983] reported similar results as they studied coal gasification in fluidized and spouted bed. They believed that it was a reflection of the presence of the high temperature zone in the spout-fluid bed where the steam/carbon reaction is more rapid. Although the H_2/CO ratio has little effect on the heating value, it would be of great significance when this pattern is observed under oxygen rather than air gasification where synthesis gases are produced.

With the rise of gasifying agent temperature, the concentrations of H_2 and CO increase, while for the concentrations of incombustible gas, such as N_2 and CO_2, a decrease can be observed in the lab-scale gasifier. The use of a high-temperature gasifying agent means more energy input to the gasifier, which allows the gasifier to operate at a much lower excess-air conditions to achieve a given reaction temperature.

With respect to the pilot plant gasifier, at higher static bed height (run 4), the fuel gas quality is greatly improved, i.e., the combustible gases contents, involving CO, H_2 and CH_4, increase, while the CO_2 and N_2 contents decrease. Higher static bed height will prolong the residence time of solid/gas in high-temperature dense zone, which favors a series of gasification reactions.

3. Gas Heating Value

The gas higher heating values (HHV) of two gasifiers are also presented in Table 5. Generally, the pilot-scale gasifier has a much higher HHV than that of the lab-scale gasifier. These deviations are caused by higher static bed height to reactor diameter (H/D) used in the pilot-scale gasifier, which leads to longer residence time in the gasification reaction zone. Another possible reason is that higher temperature in the freeboard of the pilot plant favors the dilute section gasification reactions.

4. Gas Yield

In Table 5, dry gas yield (dry basis) is displayed for both gasifiers. The dry gas yield is dependent on ER and reactions progress. As expected, the dry gas yield in the small-scale facility is higher than that of in the large-scale one due to the higher ER in the small-scale reactor. The gas yield (dry basis) in the pilot plant varies from 2.44 to 2.60 Nm^3/kg coal. Higher static bed height will produce more fuel gas due to more carbon converted to gas.

5. Carbon Conversion

The carbon conversions in two reactors are shown in Table 5. A significant difference in carbon conversion is observed. The carbon conversion in the lab-scale reactor is much higher, and higher bed height causes the carbon conversion in the pilot-scale gasifier to rise. Neither of the gasifiers have the fly ash removed by the cyclone feed back to the reactor, so all the feedstock undergoes a one step gasification process. As already mentioned above, ER in the lab-scale reactor is higher, which means more combustion reaction. As we know, the combustion reaction rate is several magnitudes greater than the gasification reaction rate, and this is one reason for higher carbon conversion in the lab-scale reactor.

Bubble behavior in a spout-fluid bed is essential to the understanding of the characteristics in different scale gasifiers. Generally speaking, gasification reactions in a low-temperature gasifier (950-1,000 °C) are kinetically controlled. Therefore, the coal gasification extent or carbon conversion is controlled by kinetics (reaction temperature and pressure) and contact time. Although the static bed height in the pilot plant is 7-12 times higher than that of lab-scale facility, the contact time is not so long as expected. The reason can be explained by a significant change of the hydrodynamic conditions due to the formation of bubbles in the spout-fluid bed. Many studies have been conducted in this area [Zhong et al., 2006a, b, c; Xiao et al., 2002]. According to the experimental results, bubble rise velocity in a gas-solid fluid bed is relative to column size. Bubbles in a smaller diameter column tend to rise slower than bubbles in a larger diameter column due to the restraining effects of the column walls. Such wall effects can be expected to diminish with increasing column diameter. This theory also considers that the gas mainly exists in bubble phase and the particles in emulsion phase. Hence, the mass transfer between bubble phase and emulsion phase is important to gas-solid coal gasification reactions. With respect to a large-scale gasifier, the gasification extent is limited by the mass exchange between bubble phase and emulsion phase due to the formation of large bubbles. In turn, a longer contact time (a higher bed height or lower gas velocity) is required in order to achieve the same conversions as in the lab-scale reactor.

6. Cold Gas Efficiency

The cold gas efficiency (on the basis of HHV) of two gasifiers is also listed in Table 5. With the higher dry gas yield and carbon conversion, the cold gas efficiency in the lab-scale reactor is slightly higher under a similar reaction and gasifying agent temperatures (run 1 and run 3). Increasing the bed height (run 4) and gasifying agent temperature (run 2) greatly improves the cold gas efficiency.

CONCLUSIONS

A 0.1 MW_{th} lab-scale and 2 MW_{th} pilot-scale gasifiers were constructed and comparative tests were carried out to study the coal partial gasification behaviors in the different scale reactors. The results show that trends obtained in the laboratory reactor are confirmed in the pilot plant operating at similar conditions, such as the $H_2/CO>1$ in the fuel gas. However, many differences are observed in gas heating value, gas yield, carbon conversion, and cold gas efficiency. These deviations are caused by the higher heat loss in the lab-scale gasifier and by different hydrodynamic conditions, which indicates the limitations of small-scale experiments. Therefore, it is obvious that a scale-up problem exists. Successful commercialization of coal gasifiers is crucially dependent on a proper understanding of the scaling up principles of spout-fluid bed, involving hydrodynamics, heat and mass transfer, and chemical reactions. It is noted that hydrodynamic conditions seem to play a more important role. In order to fully understand the scaling up principles of spout-fluid bed gasifiers, further investigations including experiments and mathematical model are required.

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