Korean J. Chem. Eng., **18**(5), 679-685 (2001)

Performance of a Pilot-Scale Gasifier for Indonesian Baiduri Coal

Yongseung Yun† and Young Done Yoo

Plant Engineering Center, Institute for Advanced Engineering,
Yongin P.O. Box 25, Kyunggi-Do 449-860, Korea
(*Received 10 March 2001 • accepted 26 May 2001*)

Abstract−An entrained-bed slagging gasifier of 3 ton/day-class was constructed in 1995 and has operated in Korea ever since. A total of nine imported coals were tested to distinguish the gasification performance with coal characteristics under high pressure conditions. Through the tests, Indonesian Baiduri coal was selected as one of the most suitable coals for the gasifier due to its high reactivity, suitable ash fusion temperature, and low ash content. For the Baiduri coal, the gasifier yields more than 98% carbon conversion efficiency and above 80% cold gas efficiency while producing about 60% CO and 30% H_2 in the nitrogen-free basis. Results show that none of the heavy metal constituents in the produced slags by the gasification is leached out by water, which is a major advantage over any combustion-based processes where ash normally contains many leachable heavy components that may contaminate the underground water eventually.

Key words: IGCC, Gasification, Slag, Cold Gas Efficiency, Indonesian Coal

INTRODUCTION

Integrated Gasification Combined Cycle (IGCC) technology, which can be applicable commercially in the near future, is regarded as a most practical next-generation coal-utilizing power generation technology along with the Pressurized Fluidized Bed Combustion (PFBC) technology that can meet the ever-stringent environmental regulations of the 21th century. The reason behind the development of IGCC technology with PFBC technology as the next-generation power generation technology is, first, that they can provide higher efficiency compared to the conventional pulverized coal combustion facility, and, second, they produce only minimal environmental pollutants well below all the current regulations. In particular, feeds that are considered as dirty feedstocks such as coal and by-products of petroleum refineries can be treated eventually as cleanly as LNG by employing these technologies. In short, the essential point of IGCC technology is that it can provide a higher efficiency along with a far better environmental performance for the feedstocks that are regarded as dirty, for example, a coal having high sulfur and/or high ash content as well as residues from petroleum refineries [Stiegel et al., 2000]. A recent simulation study [Lee et al., 1999] for the 500 MW-class IGCC plant using Korean domestic petroleum residues demonstrated that over 43% plant efficiency is possible, which is comparable with the efficiency when using bituminous coal for IGCC applications.

It has been argued that gasification systems are still too expensive, but recent rapid progress in gas turbine technologies and increased system efficiency provided greater opportunities in getting competitively priced gasification systems [Isles, 1997]. Other main reasons for delay, even after so much funding and time invested in developed countries include, from the technical point of view the following: inappropriate system connection technology and insufficient database on heat transfer values and others involving slag behavior; and from the economic point of view, IGCC technology exhibiting higher construction cost rather than that from LNG or pulverized coal power plants. However, while current construction cost has dropped to US$1,250/kW from US$2,000/kW in the '95-'96 period, further reduction is expected as low as US$1,200/kW around the 2005-2010 period. Specifically, encouraged by the fact that commercial 500 MW-class IGCC plants utilizing petroleum residues in Italy have progressed well [Collodi, 2000], Japan is promoting a 342 MW size IGCC plant with heavy residue oils. These plants clearly demonstrate the improved technical credibility of IGCC systems. It was also reported that exergy analysis technique can be applied for better efficiency in designing the complex energy systems like IGCC plants that need to minimize the avoidable energy consumption [Kim et al., 2001]. Although all the commercial demonstration IGCC plants that use coal had experienced many technical problems, they regained confidence in the technology such that developed know-how can be applied to the next IGCC plant construction cases. Here, an important point is that more technical problems are confronted for solid feed like coal far more than when liquid feed of high viscosity like petroleum residue oils is used. Even if the IGCC plant in Korea is constructed and operated, these examples indicate many technical difficulties are inevitable as exemplified by foreign experience from demonstration plants; thus, the accumulation of operation technology should be a critical ingredient domestically since the main body of operation will be performed by domestic companies. Furthermore, because the IGCC operation technology has a feature that cannot be obtained without an actual facility operating under high pressure and high temperature conditions, a pilot-scale IGCC facility as in this study can provide valuable information on the characteristics of gasification of each specific coal sample for IGCC applications.

†To whom correspondence should be addressed.
E-mail: ysyun@iae.re.kr
‡Presented at the Int'*l* Symp. on Chem. Eng. (Cheju, Feb. 8-10, 2001), dedicated to Prof. H. S. Chun on the occasion of his retirement from Korea University.

In addition, recent interest in the gasification process itself that has been renewed in many developed countries yielded several noteworthy process developments for unconventional feedstocks like biomass [Stahl and Neergaard, 1998] and wastes. United States sets the goal that will provide fuel-flexible high-efficiency power plants with virtually zero pollutants emission by 2015 through the Vision 21 program in which gasification is one of the most important key technologies to accomplish the final goal [Markowski et al., 2000].

In this study, a dry-feeding coal gasifier has been adopted over slurry-feeding type because of its operability for wide range of coal rank, especially for low rank coals of subbituminous and lignite. In general, the dry-feeding gasifier avoids the energy penalty associated with evaporating water that occurs in a slurry-feeding reactor [Nager, 1984]. Variables evaluating the gasifier performance involve coal-gas composition, carbon conversion that judges the degree of conversion from carbon in pulverized coal into gas phase carbon, and the cold gas efficiency that is the ratio of heating value in the product gas to the heating value of the feed coal.

Gasifier operation results for other coals have been reported elsewhere [Yun et al., 1998, 2000]. According to the earlier gasification tests on the nine imported coals to Korea [Yun et al., 2000], the best candidate coal for IGCC gasification applications possesses the characteristics of moderate ash fusion temperature (1,300-1,400 °C) with low-enough slag viscosity of less than 200 cp (20 Pa·s) at the operating temperature as well as the low ash content and the low fuel ratio (fixed carbon/volatile matter) in coal. Coals of the low fuel ratio are in the range of lower coal rank containing less carbon and higher oxygen. As has already been reported [Fung and Kim, 1990], the lower rank coals exhibit higher gasification reactivity in general. Among the tested coals, the Indonesian Adaro and Baiduri coals that contain the properties to fit the conditions exhibited most promising gasification results. The purpose of the study is to elaborate the detailed operational characteristics of the Indonesian Baiduri coal that was selected as one of the best coals for gasification till now under the high pressure gasifying conditions.

EXPERIMENTAL

A dry-feeding type gasifier facility, that is located at Ajou University in Suwon, Korea and can treat 3 ton/day at maximum 30 bar, 1,650 °C was built in April 1995. The facility (8 m×17 m×20 m) is located in a 30 m×50 m space. Main target feeds are subbituminous and bituminous coals, but petroleum coke is also possible to gasify. Coal feed is of identical size with that of conventional power plants using pulverized coal, as 80-90% passing −200 mesh. Pulverized coal is pneumatically conveyed with nitrogen gas in dense-phase into the feeding nozzle system, where 99%-purity oxygen and steam are mixed with the coal powder. Steam is injected separately from the oxygen and coal powder, but the current study does not use any steam, but only oxygen is employed to control the temperature and the degree of conversion. Dry-feeding gasifiers employ a maximum 15% of steam based upon the coal amount for the gasification of bituminous coals, whereas subbituninous and lignite coals normally do not need additional steam supply [Ploeg, 2000] due to their intrinsic moisture content that is stored in pores of coal structure. Thus, steam was not used in this study for the Baiduri coal which is of subbituminous rank. In general, other gasification feedstock like petroleum coke, anthracite, and petroleum residues requires higher steam addition for the gasification reaction than the bituminous coal.

Normal operation consists of the preheating, pressurization, transient operation, normal gasification operation, and the shutdown steps. LPG burner at the bottom of the gasifier did preheating of the gasifier at least for 20 hours. Then, nitrogen was introduced to pressurize the gasifier till the operating pressure range in less than 30 min; after this step, oxygen and coal powder were fed into the gasifier. Coal supply is first started at the low feeding range in order not to cause any sudden pressure buildup in the gasifier and thus causing any back pressurization into the coal feeding lines. This step takes normally less than one hour. Normal hot test operation step for obtaining gasification data is maintained at the steady state for at least 4 hours to provide enough gas, slag, and other process data. Analysis data of the Baiduri coal are as follows. Proximate analysis shows moisture 26.26%, volatile matter 32.78%, fixed carbon 37.02%, ash 3.92%, and the ultimate analysis in dry-basis shows C 69.07%, H 5.16%, N 1.29%, O (by-difference) 17.82%, S 0.79% while the coal contains calorific value of 6,367.2 kcal/kg in HHV (Higher-Heating-Value) basis.

The Baiduri coal was dried during the drying/pulverization step to less than 3% moisture content and this dried coal powder was used for gasification in the study. The combustion ash for the XRD (X-Ray Diffraction) analysis was obtained after minimum five hours of combustion in a convection oven at 650 °C. Inorganic compositions of combustion ash and the gasification slags were analyzed by XRF (X-ray Fluorescence Spectrometer, Phillips PW1480, Korea Basic Science Institute). Heavy metal concentrations were determined by ICP-AES (Inductively Coupled Plasma-Atomic Emission Spectrometer, Perkin Elmer 40, Korea Basic Science Institute) on the solution that was made by digestion with acid starting from 1 g of coal and ash samples as well as on the extracted water sample from slag. SEM (Scanning Electron Microscopy, Leica/Stereo Scan 440) was applied to see the inner shape of the produced slags, while the inner mineral structure of ash and slags was analyzed by XRD (X-ray Diffractometer, Mac Science M18XHF).

RESULTS AND DISCUSSION

Typical gasifier operating profiles are illustrated in Fig. 1; gasifier

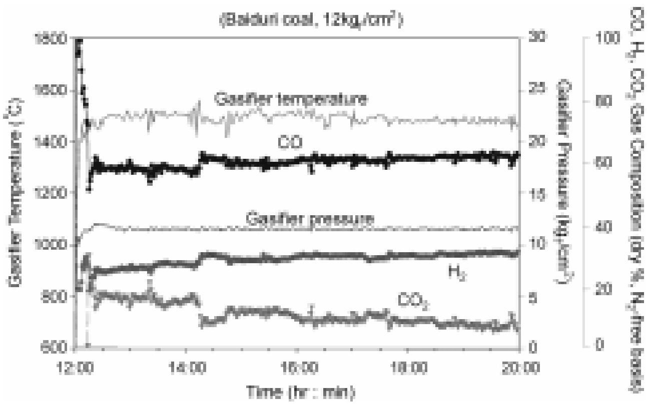

Fig. 1. Profiles of operating variables in the pilot-scale gasifier for the Baiduro coal.

pressure was controlled at a constant 12 kg_f/cm^2 while the gasifier temperature was maintained above 1,400 °C, which is required to melt the ash into molten slag. The coal-gas produced exhibits about 61% CO, 31% H_2 and around 6-9% CO_2 concentrations (nitrogen-free basis) at the optimal O_2/coal ratio range of 0.7-0.75 (0.75-0.81 in O_2/maf coal weight ratio). Normally in the pilot-scale dry-feeding gasifier, 10-30% of nitrogen that is used for pneumatic coal conveying into the gasifier exists in the coal-gas. The necessary nitrogen amount for pneumatic feeding depends upon the size of feeding nozzle, which is obviously bigger in the larger-scale gasifier. Because there's a tendency of particle blockage in the smaller-scale reactors which have a smaller feedlance diameter, higher transport velocity for particle feeding is employed in the smaller-scale gasifiers than the larger dry-feeding gasifiers. Also, in a large-scale gasifier nitrogen concentration will drop through more dense-phase particle feeding and also sometimes by replacing the nitrogen transport gas with the product coal-gas.

From the similar dry-feeding 6 ton/day-scale coal gasifier of Shell Oil Co. which has a twice capacity of the pilot-scale gasifier employed in this study, the Texas lignite coal yielded 52% CO, 27% H_2, 7.1% CO_2, 13.8% N_2 at the optimal O_2/maf coal ratio of 0.9 [Nager, 1984] that is 60.3% CO, 31.3% H_2, 8.2% CO_2 with the nitrogen-free basis, which shows the product gas composition from this study exhibits similar performance of the Shell dry-feeding gasifier. Here, maf means the moisture-ash-free basis. The CO_2 composition results from the Shell and current studies are in the lower range compared to the reported entrained-type coal gasifiers that shows about 10-12% CO_2 when CO concentration is 60% in nitrogen-free-basis. In the 0.6 ton/day-size entrained-bed gasifier test that was performed at the 5-10.5 kg_f/cm^2 pressure using the Utah bituminous coal, the product gas composition was 60% CO, 31% H_2, 9-10% CO_2 with dilution-type nozzle in inert-gas-free basis at the optimal O_2/coal ratio of 0.7-0.8 [Azuhata et al., 1986], which is also quite close data with the current study.

Some initial fluctuation in concentration in the Fig. 1 occurs due to the changes in oxygen/coal ratio and the adjusted differences in feeding conditions. Temperature shown in the figure represents the actual temperature in the gasification zone just beside the coal feeding ports and thus exhibiting some fluctuation according to the reacting coal powder and oxygen. In commercial gasifiers, this temperature is not directly measured; instead, refractory temperature slightly away from the real hot gas temperature is typically measured. Also, step changes of gas compositions in the figure are due to the adjustment in the amount of oxygen to the direction of optimal value. During the step change, CO/H_2 concentrations increases while CO_2 concentration drops, but the gasifier pressure and temperature are controlled within the set values.

Gasifiers for IGCC applications require relatively stable gas concentration with constant product gas flow whenever possible. The quality of the produced coal-gas can be represented by the cold gas efficiency whose values are shown for the Indonesian Baiduri coal in Fig. 2 as above 80% at the optimal O_2/coal ratio. Also, carbon conversion values are around 100%. Due to the measuring fluctuations, mainly in produced gas amount, carbon conversion sometimes shows above 100%. All in all, the optimal O_2/as-fed coal weight ratio that is the most important operating control variable is around 0.7-0.75 (0.75-0.81 in O_2/maf coal weight ratio) for the Baiduri coal.

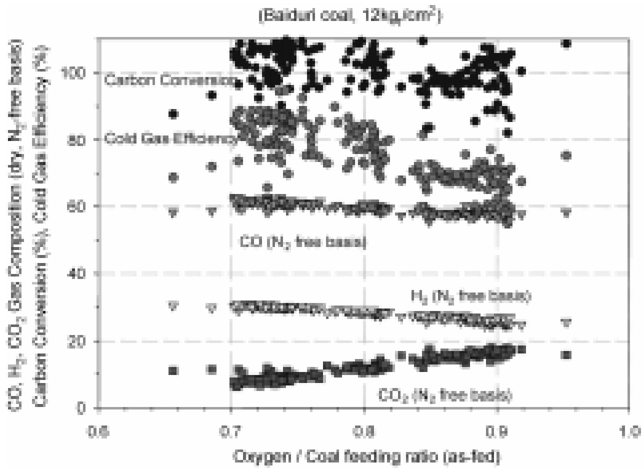

Fig. 2. Effects of oxygen/coal weight ratio for the conversion efficiencies and the product gas composition.

Here, as-fed indicates the status of coal powder just before the injection into the gasifier after the drying and pulverizing steps. From the similar dry-feeding 6 ton/day-scale coal gasifier of Shell Oil Co., maximum thermal efficiency was obtained at the 0.90 O_2/maf coal weight ratio for the Texas lignite coal [Nager, 1984] which is higher than the value from this study. This difference might be attributable to the two points: the lower moisture content of the feed just before injecting into the gasifier (3% for the Baiduri coal in this study, 12% for the Texas lignite) and lower heat loss from the reactor surface (about 3% in the reactor based upon the heat input by coal for this study and 6-7% in the Shell reactor for Texas lignite). These two factors would have the effect of reducing the required oxygen consumption for the same degree of reaction conversion.

The test yields above 80% cold gas efficiency at the optimal O_2/coal ratio conditions. Cold gas ratio is defined as the portion of the recovered energy value through the product gas that is mainly CO and H_2 over the calorific value of used coal amount. This means that more than 80% of calorific value in coal has been converted as a useful chemical energy that is maintained regardless of the following gas cooling steps. This is a significant advantage compared to the combustion process in that energy value of the product gas mainly of CO_2 will decrease with any following cooling step. Most sour gas cleanup processes that are currently available involve cooling steps associated with solvents.

Moreover, with increasing O_2/coal ratio CO_2 concentration gets higher rather faster than the decreasing trend of H_2 and CO concentrations. Also, with increasing O_2 amount for the same coal weight, the cold gas efficiency is decreasing faster than the decreasing rate of carbon conversion. Since carbon conversion involves the conversion into CO_2 that is not included in the calculation of cold gas efficiency and increased oxygen amount will just enhance the production of CO_2 from CO, the carbon conversion will remain relatively at the same value regardless of O_2/coal ratio after the optimal point.

Table 1 demonstrates the carbon conversion values of above 98% for each gasifier test that was obtained by measuring the remaining weight at different discharge ports from the gasifier system after each run. This carbon conversion result that was obtained by actual

Table 1. Mass balance by actual measurement after each gasifier run with Baiduri coal

Gasifier pressure, kg_f/cm^2	Coal fed (dry-basis)		Slag		Cyclone 1		Cyclone 2		Scrubber		Carbon conversion, %
	Amount	C %	Amount	C %	Amount	C %	Amount	C %	Amount	C %	
12	418 kg	69.7	6.2 kg	0.21	4.54 kg	23.19	1.82 kg	25.19	4.79 kg	36.50	98.9
15	231	68.4	6.0	0.14	3.12	20.62	0.77	24.56	0.94	36.26	99.3
17	377	65.8	12.0	0.02	2.12	19.91	1.33	11.34	0.65	28.78	99.7
25	564	69.9	11.0	0.31	0.23	11.15	0.49	28.23	0.04	34.34	99.9

weight measurements before and after the each experiment will be more accurate than the indirect measurement through the product gas amount and the gas composition. In the table, the amount of coal fed means the total accumulated coal use for each experiment. In addition, any possibility of settling the char in the process pipes was checked to include the amount of any unburned carbon, but gasification of Baiduri coal does not produce remaining unburned carbon in the piping system. A certain amount of slag will remain inside to coat the gasifier wall. However, slags on the gasifier inner wall were confirmed that they do not contain more than 0.2-0.4% carbon content, which in turn represents insignificant unburned carbon of less than 0.01% in total carbon conversion at the worst case. This inner-wall slag coating is the reason behind the fact that the produced slag amount from each experiment falls short of calculated slag amount from the information of ash content in feed coal when comparing the measured slag amount discharged through the slag port. When the gasifier operates continuously, the coated slag amount inside the gasifier would remain relatively constant.

Results in Table 1 show that remaining unburned carbon in slag samples is in general less than 0.3% while blown-out fines from the gasifier contain 10-40% carbon although these amounts are small. Note that 0.3% unburned carbon contained in slags is far lower than the remaining carbon in ash from the combustion processes where unburned carbon is frequently more than 5%. The high unburned carbon in the combustion ash causes problems in recycling ash for other applications along with heavy metal leaching problems.

The gasifier system consists of the gasifier, two cyclones to capture large-sized particles and the following water scrubber to retain the smaller size fines. Particle size analysis data are shown in Fig. 3. Please note that size distribution profile areas in the Fig. 3 differ with the actual captured amount since each profile area was scaled to 100%. Raw coal contains three humps in the figure at the major one at 50 microns range and the smaller humps at 10, 0.4 microns. Captured particles in the first cyclone exhibit a similar distribution pattern as the raw coal. However, from the second cyclone the distribution pattern is significantly different such that particles in the 10 micron range are captured more and even more finer particles

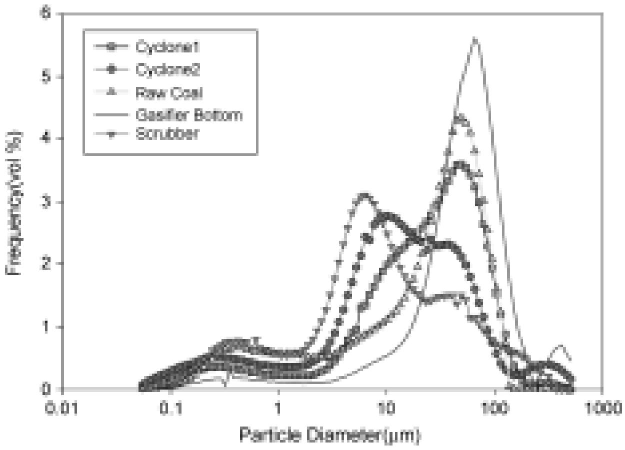

Fig. 3. Particle size distribution data for the sample from each outlet point of the gasifier system that was run at the 15 kg_f/cm^2, 1,450-1,500 °C condition with Baiduri coal.

go till the water scrubber with additional hump around 300 microns that appears probably due to particle adhesion around the molten slag particles. Even through the slag tap that is located at the bottom of the gasifier, small amounts of char particles are entrained downward so that the agglomerated bigger sizes of particles were analyzed.

Table 2 illustrates the inorganic compositions of ash after the combustion with air in an oven at 650 °C and the slags from the high pressure gasifier runs. Acidic components like SiO_2 and Al_2O_3 are more concentrated in slag, whereas SO_3 all evaporates during the gasification process yielding no more SO_3 in slags. Also, some of basic components like MgO, Na_2O, K_2O appear to evaporate in the high temperature gasification process of above 1,400 °C compared to the ash that was produced at 650 °C combustion.

Fig. 4 shows the shape and size of the slag obtained from the 17 kg_f/cm^2 gasifier run. Slags from other pressure conditions produced a similar shape and size as in Fig. 4. Biggest slag size is about 1.5 cm, and mostly they are few millimeter sizes with a sharp edge that

Table 2. Inorganic compositions of combustion ash and gasification slags after gasifier runs with Baiduri coal

Sample \ Component	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	CaO	MgO	MnO	Na_2O	K_2O	SO_3
Ash	30.3	16.8	0.68	10.04	20.7	5.02	0.12	3.73	1.07	11.54
Slag (15 kg_f/cm^2)	37.23	24.48	0.78	9.4	20.04	4.34	0.12	2.91	0.7	n.d.
Slag (17 kg_f/cm^2)	36.79	24.37	0.72	9.93	19.78	4.5	0.1	3.23	0.58	n.d.

n.d.: not detected

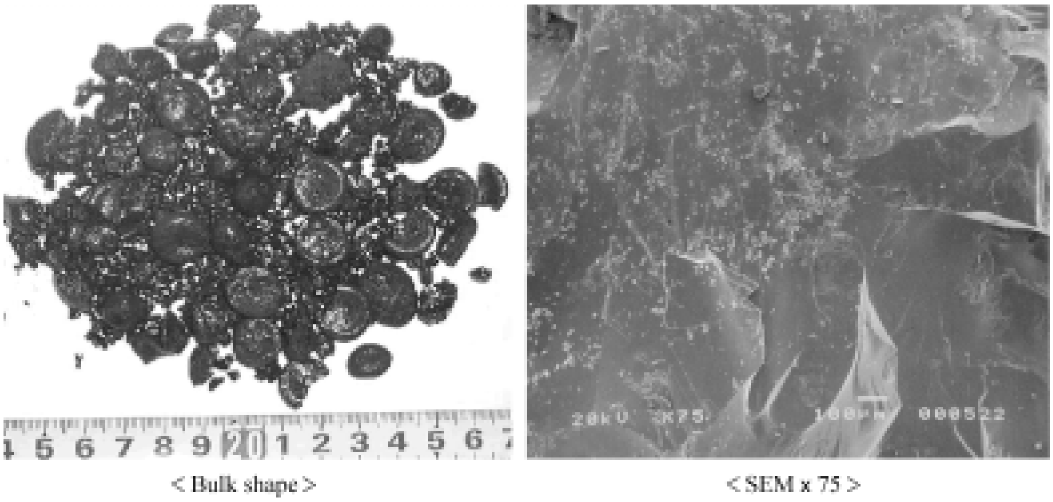

Fig. 4. Slag shape and size obtained from the 17 kg_f/cm^2 run using Baiduri coal. Left : slag picture (unit : cm), Right : Inner picture of the slag by SEM (multiplication : 75).

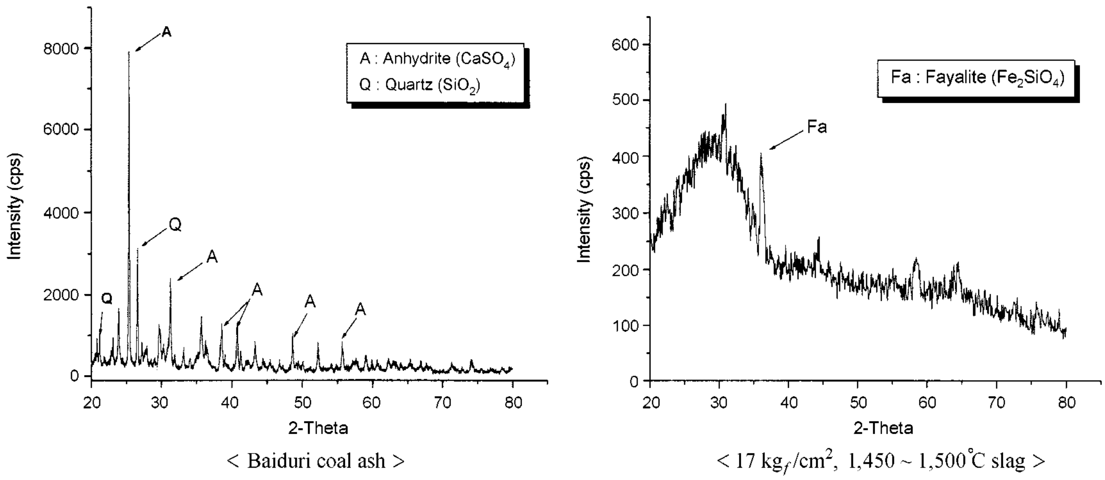

Fig. 5. XRD results of combustion ash and gasification slag for Baiduri coal.

is a typical feature of thermal shock when the molten slag flows and is quenched in water. Inner structure of the slag that is magnified by SEM appears to be structurally concrete through intertwining molten inorganic materials. While other subbituminous American Usibelli coal and several bituminous coals illustrate large number of small vesicular holes inside the slag inner surface [Yun et al., 1998], the Baiduri slag just exhibits well melted smooth inner surface. This difference is probably attributable to the characteristic difference of mineral matters under high temperature during the gasification process.

In Fig. 5, inner structure of slag can be compared with that of ash left after open-air combustion in the furnace oven. Clearly, ash exhibits the signatures of crystalline inner structure by sharp peaks in the XRD pattern, while the slag shows a rather amorphous structure that has more or less smooth XRD pattern. Thus, heavy metals and mineral components would be difficult to leach out from the amorphously intertwined molecular structure of slag. In comparison, ash of crystalline structure contains rather independently mixed heavy metals and mineral components that can easily disintegrate even by water.

Slags that were formed after melting under high temperature gasification temperature and solidification by cooling appear to bind the heavy metal components into the slag structure during the process. As shown in Fig. 5 for the slag XRD profile, heavy metal components appear to be intertwined with melted mineral matter components, so that the inner structure of slag is amorphous. Heavy metal components of Cr, Ni, Co, Mn, Ga, Cu, Sr, Ba, Zr, V concentrate in slags, whereas Hg appears to evaporate so that Hg concentration in slag is lower than the raw coal. Evaporated Hg has to be captured in the following gas cleanup processes that are mainly employed to remove H_2S and NH_3 produced by gasification. In the gasification process, H_2S and NH_3 are produced instead of exhaling polluting SO_x and NO_x by combustion. Large portion of Cr in slag seems to originate in part from the refractory component of Cr_2O_3 contained in the refractory about 52% that is added for the higher temperature service in the reducing environment. Even with possible Cr detachment from the refractory wall under high temperature gasification reactions via reactions with slags, the refractory itself has not presented any structural problems at least during the one year test period, maybe by the protection of slag layer around

Table 3. Comparison of heavy metal contents in the raw Baiduri coal, combustion ash, slag from the gasifier, and in the extracted water from slag

Heavy metal component, ppm	Raw coal	Ash	Slag	Extracted water from slag	Slag	Extracted water from slag	Korea's wastewater standard
			15 kg_f/cm^2, 1450-1500 °C		17 kg_f/cm^2, 1450-1500 °C		
Cr	30.13	447.95	7760	0.081	8840	0.031	0.5
Zn	49.44	792	49.87	0.032	12.82	0.05	5.0
Cd	0.151	0.187	0.94	<0.005	<0.005	<0.005	0.1
Pb	3.344	68.65	2.841	<0.005	1.14	<0.005	1.0
Ni	10.35	166.25	151.05	0.018	153	0.019	
Co	2.151	37.86	31.1	<0.005	39.15	<0.005	
Mn	50.95	907.5	895.5	0.008	834.4	0.0097	10
Ga	8.17	125.45	104.4	0.009	90.68	0.01	
Cu	25.24	456	231.55	<0.005	246.16	0.014	3.0
Sr	121	2548	2455.5	0.091	2353.2	0.059	
Ba	160.7	2895.5	2638	0.2085	2911.2	0.292	
Zr	<0.005	99.6	3401	<0.005	2416	0.016	
Hg	2.081	0.25	0.333	<0.005	0.7	<0.005	0.005
As	4.602	37.36	7.065	<0.005	<0.005	<0.005	0.5
Se	0.178	4.091	2.965	<0.005	1.26	<0.005	
Sb	0.142	2.621	0.159	<0.005	2.4	<0.005	
V	9.955	158.3	195.5	<0.005	150.36	<0.005	
Sn	2.501	33.15	3.468	<0.005	<0.005	<0.005	

the inner gasifier wall. More detailed analysis on the mechanism of Cr migration is under study and will be reported later.

In Korea, heavy metal components like Cr, Zn, Cd, Pb, Mn, Cu, Hg, As are regulated as pollutants in the leached water. According to the leaching test on the produced slags, these heavy metal components were detected far below the environmental regulation values as illustrated in Table 3. Concentrated heavy metals in slags cannot break away from the intertwining molecular structure by mild solvent like water. Thereby, coal slag can be safely utilized as a construction material or filler for road and proved not to cause any secondary pollution in groundwater. Usually, coal flyash from a boiler causes a secondary pollution by leaching of heavy metals.

CONCLUSIONS

Indonesian Baiduri coal of subbituminous rank was selected as one of the most suitable coals for IGCC applications among the tested eight coals of bituminous and subbituminous ranks in the 3 ton/day-size pilot gasification plant. The coal showed efficiencies that are above 98% in carbon conversion and above 80% in cold gas efficiency. Product gas exhibits concentrations of about 60% CO, 30% hydrogen, and 6-9 CO_2 in a nitrogen-free basis that are comparable concentrations with reported values from 0.6-6 ton/day coal gasifiers. Optimal oxygen/coal weight ratio, which is the most important control variable in the gasifier operation, was found to be in the range of 0.7-0.75, which is also in good agreement with reported values in entrained-bed coal gasifiers of 0.6-6 ton/day size.

Entrained fines from the gasifier contains 10-40% remaining carbon, although the amount was small to influence the total carbon conversion. Obtained slag shows a size of less than 1.5 cm with mostly sharp edges that is a typical feature of water-quenched slag. Furthermore, slags contain less than 0.3% unburned carbon, which is far lower than the ash from the combustion processes where unburned carbon is frequently more than 5%. Acidic inorganic components like SiO_2 and Al_2O_3 are concentrated in slag compared to the combustion ash, while all of SO_3 component and most of Hg seem to evaporate during the gasification process. Inner surface of Baiduri slag that shows relatively smooth melting behavior looks quite different with inner surfaces of other slags from different coals where a signature of vesiculation is dominant. Slag structure was analyzed by XRD in which amorphous characteristics were obvious in the gasification slags compared to the crystalline structure shown in combustion ash. Slags were confirmed not to produce any secondary water leaching problems and thus can be utilized safely as road filler.

ACKNOWLEDGEMENT

The R&D Management Center for Energy & Resources, Korea supported this work with the research title of Development of Operation and Simulation Technologies for the Bench Scale Coal Gasifier (II).

REFERENCES

Azuhata, S., Hedman, P. O., Smoot, L. D. and Sowa, W. A., "Effects of Flame Type and Pressure on Entrained Coal Gasification," *Fuel*, **65**, 1511 (1986).

Collodi, G., "Operation of ISAB Energy and SARLUX IGCC Projects," Proc. of 2000 Gasification Technologies Conf., San Francisco, U.S.A. (2000).

Fung, D. P. C. and Kim, S. D., "Gasification Kinetics of Coals and

Wood," *Korean J. Chem. Eng.*, **7**, 109 (1990).
Isles, J., "Keep More than Just an Eye on IGCC," *Modern Power Systems*, **17**(2), 15 (1997).
Kim, J. J., Park, M. H. and Kim, C., "Performance Improvement if Integrated Coal Gasification Combined Cycle by a New Approach in Exergy Analysis," *Korean J. Chem. Eng*., **18**, 94 (2001).
Lee, S. J., Yun, Y., Yu, J. Y. and Seo, I. J., "Performance Evaluation of Heavy Residual Oils in the 500 MW IGCC Plant," *HWAHAK KONGHAK*, **37**, 775 (1999).
Markowski, J. J., Archer, D. H., Balzhiser, R. E., Brand, D. A., Espino, R. and Iglesia, E., "Vision 21 - Fossil Fuel Options for the Future," National Academy Press, Washington, D.C. (2000).
Nager, M., "Evaluation of U.S. Coal Performance in the Shell Coal Gasification Process - Volume 1: Texas Lignite," EPRI AP-2844, Vol. 1, Research Report Center, Palo Alto, CA (1984).
Ploeg, J., "Gasification Performance of the Demkolec IGCC," Proc. of Gasification 4 the Future, Session 3-1 Paper (2000).
Stahl, K. and Neergaard, M., "IGCC Power Plant for Biomass Utilisation, V‰rnamo, Sweden," *Biomass and Bioenergy*, **15**(3), 205 (1998).
Stiegel, G. J. and Maxwell, R. C., "Gasification Technologies: The Path to Clean, Affordable Energy in the 21st Century," *Prepr. Paper - Am. Chem. Soc., Div. Fuel Chem*., **45**(1), 102 (2000).
Yun, Y., Yoo, Y. D., Lee, H. G. and Chung, S. W., "Performance of a 3 Ton/Day Coal Gasifier under High Pressure Conditions," Proc. of 2nd Korea-China Joint Workshop on Coal and Clean Energy Utilization Technology, Taejon, Korea, 311 (1998).
Yun, Y., Yoo, T. D. and Chung, S. W., "Effects of Coal type on the Gasifier Performance," Proc. of 3rd Korea-China Joint Workshop on Coal and Clean Energy Utilization Technology, Taiyuan, China, 99 (2000).