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Operation characteristics of 1 ton/day-scale coal gasifier with additional stage

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Abstract−A one-stage coal gasifier was modified to accommodate the two stages of coal feeding. Operating characteristics were compared between the one-stage and two-stage gasification in terms of syngas composition, carbon conversion, shape and inner structure of produced slags, characteristics of particle size distribution in entrained fines, and effects on particulate removal facilities. Temperature at the second stage of the gasifier resulted in lower values, which confirms the performance of the second stage as a reduction area by endothermic reactions. The results suggest that the 10-20% increase in coal feeding to the second stage might not cause much loss in carbon conversion. Produced slag and the performance of metal filters and water scrubber were similar with the earlier results from one-stage gasification tests. The two-stage gasification appears to help in increasing the cold gas efficiency for the certain operating range. Two-stage gasification had an impact on the 0.1-1 μm size of entrained fines, which appear to be cenospheres that occur during the rapid quenching in temperature.

Key words: Coal, Gasification, Two-stage, Cold Gas Efficiency, Cenosphere

INTRODUCTION

Coal can provide enough energy that society needs for the next 200 years with the current energy consumption rate. The International Energy Agency also pointed out that coal should play a pivotal role for electricity generation until 2030 [1]. Even with increasing demand and technological developments in renewable energy fields like photovoltaic and wind, it is expected to take at least 30 years until the renewable energy can act as a large scale energy provider. Eventually, renewable energy would gradually replace fossil energy with the introduction of distributed electricity grids. But, the problem is how to provide enough electricity in a large scale without causing environmental and climate-related problems.

Coal should be utilized to the level of natural gas in environmental and CO_2 related points. To use coal for the next 30-50 years, the CO_2 issue should be solved. Currently, the electricity generating sector comprises about 30% of global CO_2 emission [2], which means that without curbing CO_2 emission amount from this sector, especially power plants using coal, controlling CO_2 emission would not be easy as a whole.

To cope with pollutants and CO_2 issues arising from coal utilization, clean coal technologies have been demonstrated and deployed from the 1990's. Among clean coal technologies, Ultra super-critical (USC) and integrated gasification combined cycle (IGCC) technologies are front runners. Pressurized fluidized-bed combustion (PFBC) technology is not widely accepted as a candidate for big-scale power generation technology, mainly due to low construction demand during the last two decades and the inherent limitation on CO_2 issue since it is based upon combustion and quite different configuration compared to the conventional plants based on the pulverized coal combustion.

Coal gasification has merits in several ways, but also with disadvantages in higher construction cost and lower plant availability even after several demonstration experiences around the world. Yet gasification should remain as a major contributor in coal utilization, especially in a CO_2-conscious trend.

USC and IGCC technologies all intend to increase the net efficiency for electricity generation from coal to the level of 45-50%. IGCC can exhibit efficiency above 60% when it is combined with fuel cell technology in the future, that might be around 2030.

There is a distinct trend in gasifier development by area. In the USA, commercially available gasifiers of GE Energy (former Texaco) and ConocoPhillips are all based on the slurry feeding method. While all European commercially available gasifiers of Shell, Siemens (former Future Energy), Plenflo are based on the dry-feeding method. Japanese gasifiers are all based on the two-stage CRIEPI gasifier concept and diversified into Mitsubishi and Hitachi two-stage gasifiers. The Mitsubishi gasifier is the only gasifier system that employs air (actually 25% oxygen-enriched air) instead of oxygen for gasification.

The two-stage gasifier has several advantages and disadvantages. The key disadvantage is the increased capital cost due to complex feeding system in addition to the operational complexity. However, the many advantages outweigh the disadvantages. Key advantages reside in the enhanced ability to handle many different types and quality coals and the distribution of coal feeding load to several nozzles instead of one set of nozzles as in the Shell gasifier or just one feeding nozzle as in the GE Energy gasifier or Siemens gasifier cases. One of the most important areas of development in reducing the gasifier downtime is the improvement in the lifetime of coal feeding nozzles. In many commercially sold gasifiers, it is known that the nozzle is sometimes replaced every six months or at least once a year.

For electricity generation in Korea, all bituminous and subbitumi-

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nous coals are imported, while a small amount of low grade Korean anthracite is employed in local CFBC power plants. From the year 2007 in Korea, variability of coal quality in imported coals increased significantly and the probability of mixing different coals for coal power plants has been increased also greatly. In this regard, the two-stage gasifier has many useful aspects to explore in Korea's circumstances.

The aim of the paper is to verify the operability of two-stage gasifier in a pilot scale in terms of conversion efficiencies, coal feeding, any tendency in blockage of slag-tap or gasifier exit pipe, the amount and characteristics of entrained fines, and characteristics of produced slag.

EXPERIMENTAL

1. Coal Sample

Indonesian subbituminous ABK (Anugerah Bara Kaltim) coal was employed as a test coal. Table 1 illustrates detailed analytical data for the tested coal, which illustrates the coal properties for the pulverized coal that is dried for pneumatic feeding to the dry-feeding gasifier. The coal shows the fluid temperature of ash is only at 1,190 °C,

Table 1. Analysis data of Indonesian ABK (Anugerah Bara Kaltim) coal

Proximate analysis (wt%)[a]	Moisture	3.8
	Volatile matter	41.23
	Fixed carbon	45.93
	Ash	9.04
Ultimate analysis (wt%)[b]	C	66.51
	H	4.89
	O[c]	17.65
	N	1.34
	S	0.22
	Ash	9.39
Ash fusion temperature (°C)	IDT	1160
	ST	1170
	HT	1180
	FT	1190
Higher heating value[b] [kcal/kg]		6021.9

[a] Dry basis
[b] Moisture-free basis
[c] By-difference

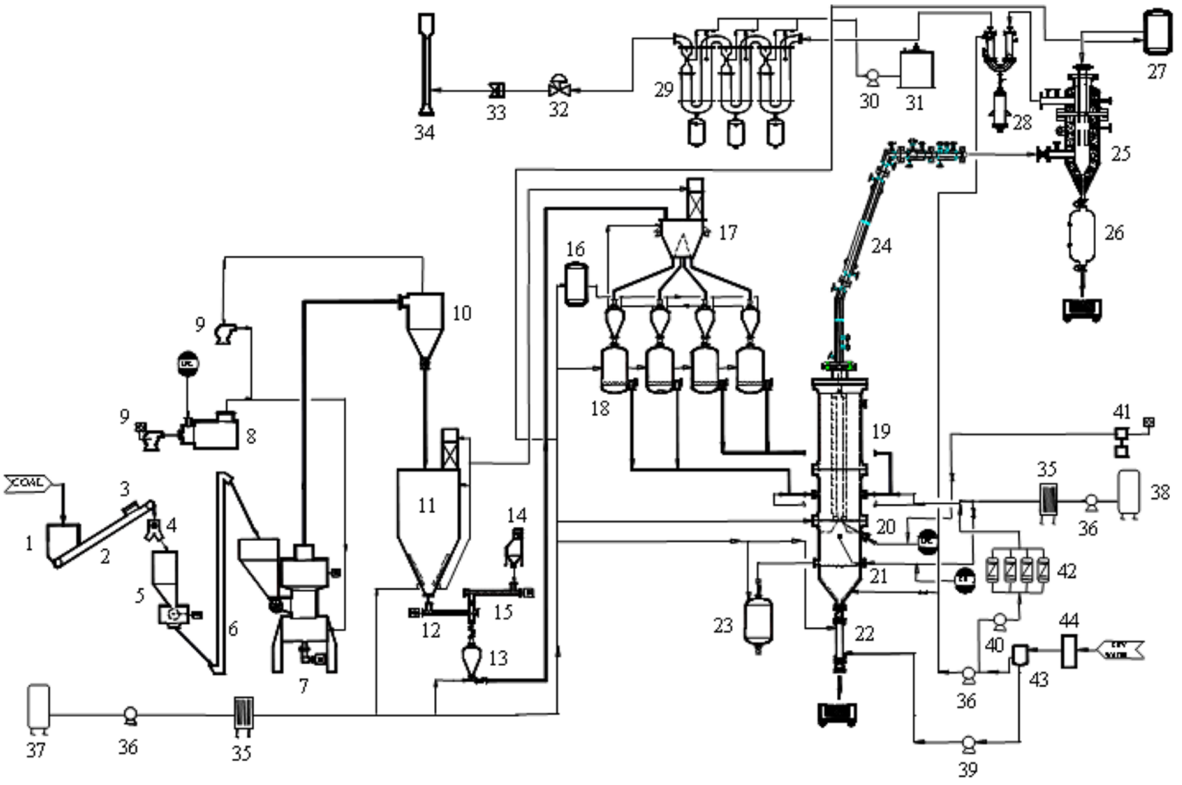


Fig. 1. Process flow diagram of pilot-scale coal gasification system.

1. Vibration feeder
2. Belt conveyor
3. Magnetic seperator
4. Metal detector
5. Crusher hood
6. Bucket elevator
7. Coal pulverizer
8. Air preheater
9. Fan
10. Bag house
11. PC bin
12. Screw feeder
13. Denseveyor
14. Flux station
15. Flux metering feeder
16. H.P nitrogen storage tank
17. Distribution hopper
18. Controlveyor
19. Gasifier
20. Start-up bumer
21. Methane bumer
22. Slag lockhopper
23. Water receiver
24. Syngas cooler
25. Filter system
26. Ash lockhopper
27. H.P nitrogen tank
28. Wet scrubber
29. Desulfurization system
30. H.P pump
31. Fe chelate storage tank
32. Pressure control valve
33. Flame arrestor
34. Flare stack
35. Vaporizer
36. H.P pump
37. Liquid nitrogen tank
38. Liquid oxygen tank
39. L.P pump
40. Metering pump
41. Air compressor
42. Steam generator
43. Water suction tank
44. Water treatment

which is in a low range for the proper slagging in the pilot-scale gasifier.

2. Gasification Facility and Procedure

A dry-feeding entrained-bed type gasification facility, which is located at Ajou University in Suwon, Korea and is capable of treating 3 ton/day at maximum 28 bar, 1,550 ºC, was built in April 1995. A process flow diagram of the facility is shown in Fig. 1. The main target feeds are subbituminous and bituminous rank coals. Coal feed size range is identical with that of conventional power plants using pulverized coal, as 80-90% passing −200 mesh.

Coal powder was dried during the pulverizing step for less than 4-7% moisture content depending on the moisture content of raw coal. Pulverized coal is pneumatically conveyed with nitrogen gas at 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 pulverized coal. In the study, coal feeding rate of 40 kg/h was maintained for the one-stage operation, after which the two-stage operation was performed at the 50 kg/h rate with the additional 10 kg/h. The operated pressure of the gasifier was 8 kg/cm^2.

Applied metal filters are based on the sintered mesh type of SUS 316L. Five layers of the meshes were pressed to manufacture the metal filter of 1,500 mm height, 60 mm outside diameter.

Major operational variables of the gasification were the oxygen/coal weight ratio and temperature inside the gasifier. Normal operation consists of the preheating, pressurization, transient operation, normal gasification operation, and the shutdown steps. The LPG burner at the bottom of the gasifier did the preheating of the gasifier at least for 20 hours. Then, nitrogen was introduced to pressurize the gasifier till the pre-set gasifier pressure before injecting the oxygen and coal powder. The current study did not use any steam, but only oxygen was employed to control the temperature and the degree of conversion.

Injection of coal powder into the gasifier was first started at the low feeding range so that no sudden pressure buildup would take place in the gasifier, thus causing no back pressurization into the coal feeding lines. This step took normally less than 1 hour. The normal hot test operation step for obtaining gasification data was maintained at the steady state for at least two hours to provide enough gas, slag, and other process data. Gasifier temperature was measured with R-type thermocouples which were positioned along the inside gasifier wall which contacted the syngas directly.

For the two-stage operation, an additional one stage section was inserted just above the first stage feeding section. The addition of one more gasifier section increased the total volume of the gasifier by 40%. The test was done with the first-stage operation at the 40 kg/h feeding condition. After reaching steady state by the first-stage operation, additional coal powder of 10 kg/h was injected through the two opposed feeding nozzles at the second stage. During the one-stage operation with the first stage feeding section, oxygen of 1.5-2 Nm^3/h was fed to the second-stage nozzles with 10 Nm^3/h nitrogen in order to prevent any blockage in the feeding lines at the second stage. During the two-stage operation, oxygen amount to the second-stage feeding nozzles was increased to 6-7 Nm^3/h and the nitrogen amount was maintained at the same 10 Nm^3/h.

3. Gas Analysis

On-line gas analyzers connected to the gasification system provide an instantaneous gas composition of H_2, CO, CO_2, CH_4, and the additional on-line gas chromatography (MTI Analytical Instrument, P200H) gives more precise quantitative gas composition with 3-minute intervals.

RESULTS AND DISCUSSION

One more stage of gasification zone was added to the pilot plant gasifier of the one-stage dry-feeding entrained-bed. As explained in the introduction, there are several features that two stages of gasification could be better when many different sources of coals should be used, especially for coals exhibiting wide variation in coal quality. Basically, the two-stage gasifier can handle coals of widely different qualities by recycling the un-reacted part of the coal while sacrificing the increased complexity of more feeding nozzles and related capital cost.

To study the operating characteristics of a two-stage gasifier, An Indonesian subbituminous coal was gasified for nine hours. At first, dried pulverized coal was injected into the gasifier with two opposite nozzles to increase the gasifier temperature above the slagging temperature. For the tested ABK coal, the fluid temperature of ash was measured as 1,190 ºC, which means that the gasifier operating temperature should be maintained at least above 1,240 ºC.

As a first series of tests to verify the operability of two-stage gasifier, the results shown here are focused on the temperature variation with adding feeding nozzles above the first feeding nozzles as well as the characteristics of captured fines that are supposed to be recycled into the gasifier. The added feeding nozzles were also located at the opposite position of the gasifier inside circle.

Fig. 2 shows the profiles of key gasification parameters of gasification pressure, temperature inside the gasifier, and the produced syngas flow rate. Gasification pressure was maintained at the 8 bar condition, and the gasifier temperature was in the 1,200-1,400 ºC range. During the initial gasifier operation, the gasifier was operated as one-stage in that coal feeding lines were aligned at one height level of the gasifier. After about two hours of the normal one-stage operation, upper feeding lines were used to supply the additional 25% of coal powder into the gasifier. With the change to two-stage operation, the syngas flow rate was increased from about 90 Nm^3/h

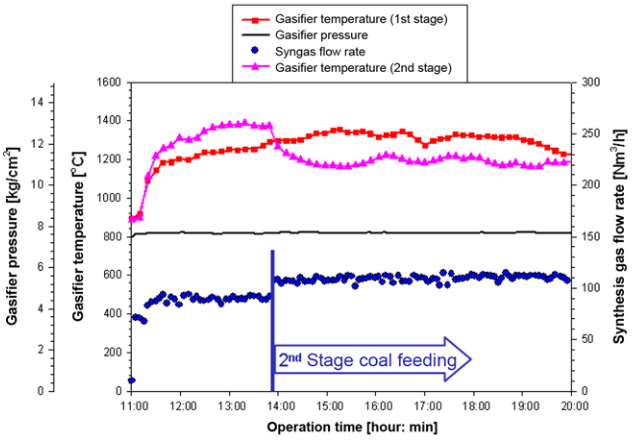


Fig. 2. Operating profiles of key parameters in the two-stage gasifier.

to 110 Nm^3/h as illustrated in Fig. 2. This increase in syngas flow was attributed to the syngas amount produced by the 25% additional coal input to the gasifier. Here, the increased rate in syngas flow does not directly match to the increase in coal feed rate, because the nitrogen that is employed for pneumatic conveying of pulverized coal exists in syngas at 30-40% range. In the bigger scale gasifier, this nitrogen amount for pneumatic conveying would decrease dramatically since the wall effect by small pipe is minimized.

Switching to two-stage operation, the temperature at the second stage dropped from 1,380 °C to the level of 1,200 °C, while the gasifier temperature at the first stage (main reaction zone) steadily increased from 1,200 °C to the 1,350-1,360 °C level. When additional coal was supplied to the second stage of the gasifier, endothermic reactions such as the carbon-steam reaction ($C+H_2O \rightarrow CO+H_2$), Boudouard reaction ($C+CO_2 \rightarrow 2\ CO$) resulted in lower temperature. This is the reason the second stage gasifier section is called a reductor which causes to drop the temperature. Advantages of introducing the two-stage gasification system can arise from the fact that unnecessary components (H_2O and CO_2) can be converted to the useful components of CO and H_2 by these reactions before syngas is exiting the gasifier while reducing the gasifier exit gas temperature.

In the normal gasifier operation of dry-feeding gasification, gasifier exit gas temperature is better to be lower than 900 °C, because above 900 °C fly-slag would remain as a sticky form in that fully or half melted slag droplets would fly out from the gasifier and ended up in accumulating on any cold surfaces after the gasifier, which is typically radiant gas cooler and the connecting tube between the gasifier and the gas cooling device. At the worst case, whole syngas flow pass could be blocked by accumulated sticky fly-slags.

Disadvantages of second stage operation of gasifier yielded higher amount of particulates that needed to be captured and recycled if necessary to reach above the 99% carbon conversion that is a typical standard of commercial gasifiers. Percentage of the particulates captured by the high temperature metal filters was 3.5% of the raw feed coal that had been injected into the gasifier, as illustrated in Table 2. Fines captured by the metal filters contain about 29% carbon as shown in Table 2. When the amount of fines is high enough to contribute to the carbon conversion loss significantly, the fines have to be recycled to the gasifier. In terms of carbon conversion, the amount captured at the filter hopper contributes 1.03% (3.5×0.2914) loss of carbon conversion. In earlier studies [3-5] on the one-stage gasifier operation with the same gasifier, carbon conversion with one-stage gasification was above 99% for Indonesian Baiduri and Adaro coals which are all in subbituminous rank as the ABK coal. Additional 25% increase of coal feeding amount to the second stage of the gasifier yielded the carbon conversion loss of few tenths of one percent, which suggests that the 10-20% increase in coal feeding to the second stage might not cause much loss in carbon conversion. In Japanese cases on the two-stage gasification (CRIEPI gasifier [6], Mistubishi Heavy Industry gasifier [7]), the 40-50% of total coal feeding amount is injected through the second-stage reduction section, and the captured char particles are recycled to obtain the carbon conversion of above 99.5%. When the feeding rate to the second-stage reduction section is increased as in Japanese two-stage gasifiers, the tested two-stage gasifier also needs to recycle the captured fines for the 99.5% carbon conversion.

Table 2. Fines captured at different location of gasification system (ABK coal)

Sampling location		Raw pulverized coal	Syngas cooler inlet	Filter hopper
Proximate analysis (wt%)^a	Moisture	3.8	0.21	5.56
	Volatile matter	41.23	2.68	0
	Fixed carbon	45.93	0.34	28.64
	Ash	9.04	96.77	65.8
Ultimate analysis (wt%)^b	C	66.51	2.54	29.14
	H	4.89	0.06	0.21
	O	17.65	0	0
	N	1.34	0.16	0.11
	S	0.22	0.27	0.87
	Ash	9.39	96.97	69.67
Amount of feed, fines (kg)^b		552		19.5 (3.53% of raw coal)

^{a}Dry basis

^{b}Moisture-free basis

Fig. 3 shows the coal gas composition from the gasification test of the pilot scale unit operated at the 8 bar pressure. Syngas is comprised mainly of CO and hydrogen at about 36% and 12% from the one-stage operation in dry basis. At the two stage operation, the CO and hydrogen concentrations increased to 43% and 18%, while the CO_2 concentration dropped from 12% to 7%.

Conversion efficiencies based upon the syngas composition shown in Fig. 3 are illustrated in Fig. 4. With the one-stage operation, carbon conversion remained only at 80% and the resulting cold gas efficiency was in the range of 48-50%. When 25% more coal was fed into the second stage gasifier section, the carbon conversion moved upward to reach 90-92%, while the cold gas efficiency shifted to the 65% range. These results clearly indicate that a proper introduction of additional coal powder into the second stage could increase the gasification efficiencies. It should be noted that the result shown here employed an additional 25% of the total coal feeding amount to the second stage nozzles. Future tests on increased feeding amount to 50% as in Japanese cases would provide more concrete modifi-

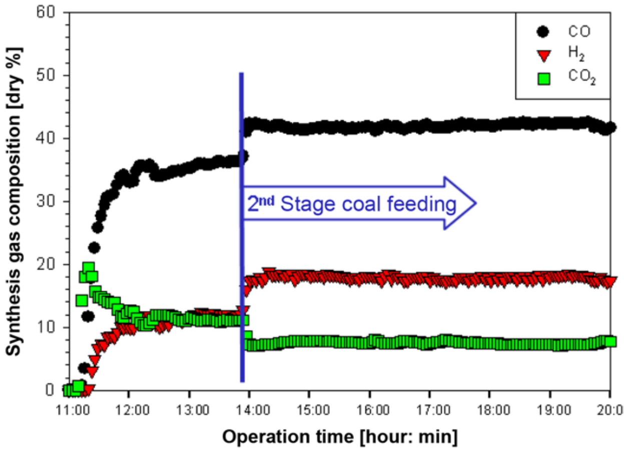


Fig. 3. Syngas composition changes in the two-stage coal gasification.

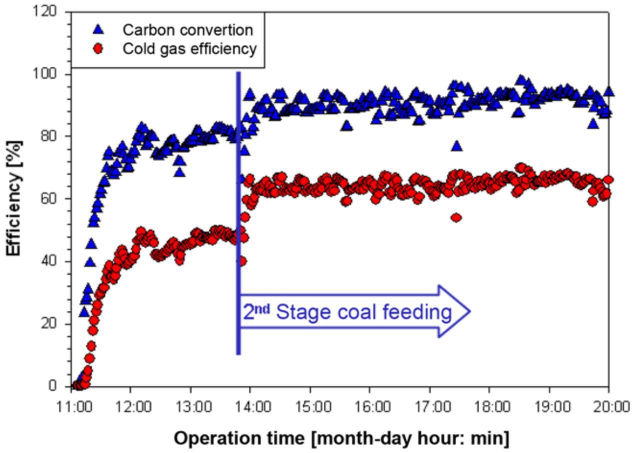


Fig. 4. Changes in cold gas efficiency and carbon conversion by the two-stage gasification.

cation of inner design in the two-stage gasifier, and the effects of fines recycle on the overall efficiencies. At least it can be concluded that the two-stage gasification appear to help in increasing the cold gas efficiency for the certain operating range.

Fig. 5 shows the shape of slag formed from the two-stage coal gasifier at the 8 bar pressure. Right-hand side picture in Fig. 5 exhibits the enlarged view of the slag. Slags produced from the two-stage gasifier show a similar shape and sizes as the slags from the one-stage gasification for the Indonesian subbituminous Baiduri coal [3]. Most slag shape resembles round beads of few millimeters size at the maximum diameter of about 1 cm with cracked pieces out of the round bead shape of slags. This kind of slag shape is formed when the slag is cooled in a rather slow speed instead of directly dumped into the cold water. Also, slags of cracked shape are shown in the figure. The cracked shape was produced while the molten slag dropped into the cold water at the bottom of the gasifier and exploded with thermal shock. In general, the shape of slag is determined by the quenching speed, not by the gasification pressure condition.

As demonstrated in Fig. 6, heavy metal components appear to be intertwined with melted mineral matter components, so that the inner structure of slag is amorphous. The XRD pattern on the slags from the two-stage gasification clearly demonstrates the amorphous structure without any clear crystalline signature by mineral components. Typically, the combustion ash exhibits several sharp peaks of crystalline signature in the XRD profile. In terms of slag size and inner structure, the two-stage gasification showed the similar result as in the one-stage gasification.

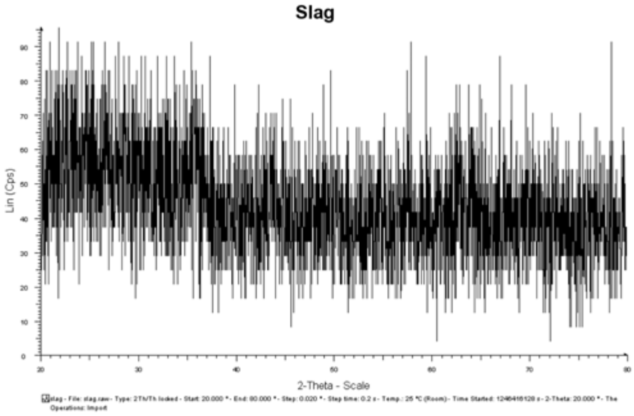


Fig. 6. XRD analysis on slag from ABK coal gasification.

Table 3. Analysis data of slag from gasification of ABK coal

Proximate analysis (dry basis, wt%)	Raw coal	Slag	
		Less than 1 mm	Over 1 mm
Fixed carbon	47.76	10.06	0
Volatile matter	42.85	5.08	0.53
Ash	9.39	84.86	99.47

Slags possessed normally less than 0.3% carbon content for other tested coals while showing no elutriation of heavy metals by water [3]. Table 3 shows the proximate analysis results on slags of over 1 mm and less than 1 mm size. The slag of over 1 mm size does not contain any remaining carbon while the small size slags less than 1 mm contain about 10% residual carbon. The amount of small size slag was less than 15% of the total produced slag amount.

A coal gasifier should be able to convert the 98-99% of carbon into syngas of CO and hydrogen while the inorganic components are produced mostly as a slag. A portion of molten slag and ash is entrained with syngas flow to exit the gasifier and reach the particu-

Fig. 5. Slag from ABK coal gasification (unit: cm, mm).

late removal and heat exchanging equipment.

In the two-stage gasifier, entrained coal fines are supposed to be recycled as a char. If the total remaining carbon in the captured fines is less than about 0.5%, it should be decided whether the fines should be recycled or just discarded as a waste, or sent to the cement industry as a useful ingredient. Most of the combustion coal ash that contains less than 5% carbon content in Korea are recycled as a raw material for cement ingredient or other forms. If the total remaining carbon is higher than 1%, then recycling of captured fines should be considered. When the gasifier handles few hundred tons of coal, even few percent of total remaining carbon in fines can be acceptable for just discarding or shipped to cement industry. But, when the gasifier is used for IGCC application, the 2,000-3,000 tons of coals are gasified every day and the remaining 1% total carbon means 40-60 tons of fines per day (assuming 60% carbon in raw coal, 30% carbon in gasified fines) to dispose. For IGCC application, definitely full recycling is required to minimize the disposal amount as particulate fines instead of environmentally safer slags.

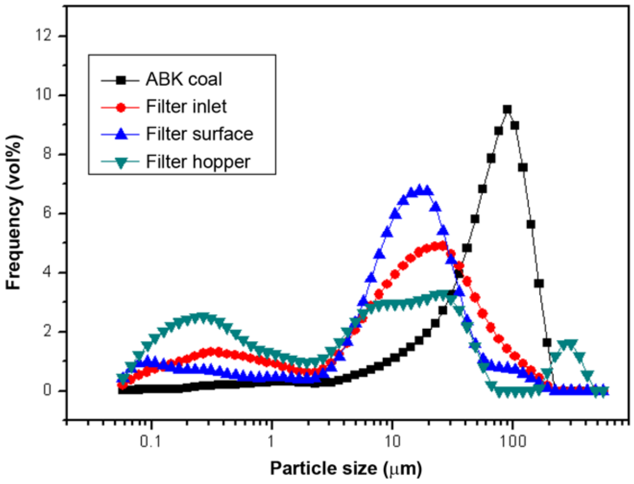
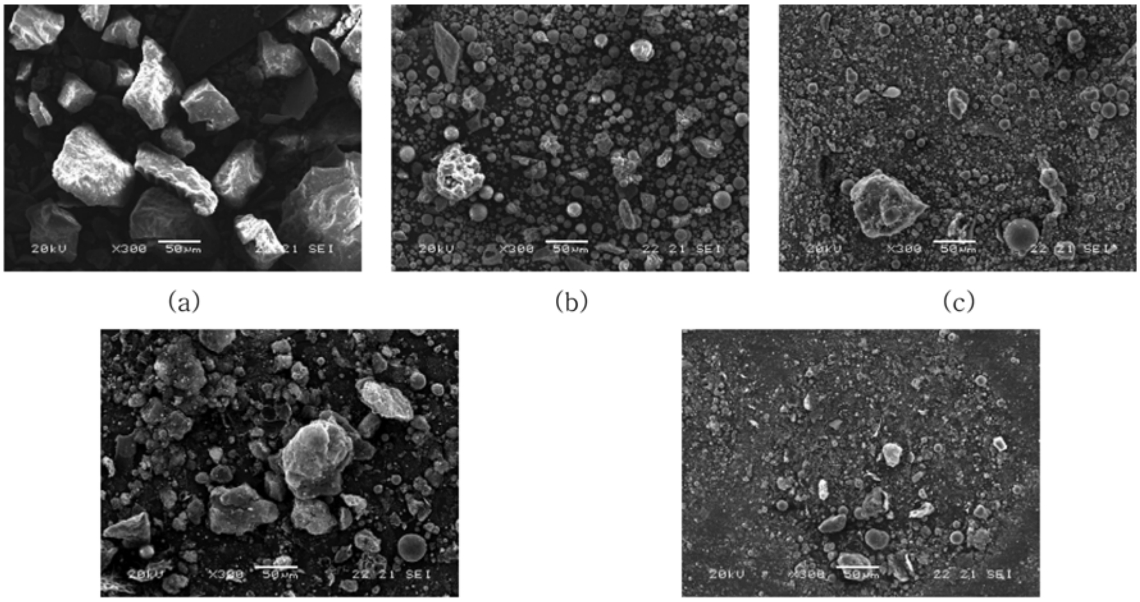


Fig. 7. Particle size distribution of ABK raw coal and captured fines.

Fig. 7 illustrates the particle size distribution of raw coal and the captured fines at different locations of the gasification system. Raw ABK coal shows the highest peak at about 90 μm with increasing frequency from 3-4 μm and no visible size above 200 μm. In contrast, fines captured around the metal filters distinctively show bimodal peak shapes at about 0.2 μm and about 15 μm regions. Fines captured by the metal filters show the additional peak at 200-500 μm range. This additional peak most probably occurred by loosely agglomerated particulates.

Most important data in Fig. 7 are the one for the particulate fines captured at the filter hopper, which are supposed to be recycled into the gasifier. Captured fines at the filter hopper contain 0.1-1 μm fines, 7-30 μm size particulates, and a small peak above 200 μm size. Compared with the earlier report [3] that was for the similar Indonesian subbituminous Baiduri coal, the relative peak height at 0.1-1 μm range to the 7-30 μm range was about three times higher in the two-stage gasification test of this study. Whether this three times variation attributes to the inherent characteristics of raw coal or to the additional feeding through the second stage gasifier needs to be studied more, but it appears that two-stage gasification had an impact on the increased frequency in the 0.1-1 μm size of fines.

Fig. 8 demonstrates the SEM pictures of the raw coal as well as the pictures on the particles captured from the gas cooler to the filter hopper. Magnification of all SEM pictures is identical as 300 times. Particles obtained from the gas cooler inlet are shown in Fig. 8(b). The location of gas cooler inlet is just after the gasifier exit as shown in Fig. 1. After the reaction in the gasifier, large numbers of small spheric particles and aggregates of small fines are shown in entrained fines. The SEM picture (Fig. 8(c)) on the fines obtained at the inlet pipe just before entering the metal filters also exhibits small spheric



(a) (b) (c)

(d) (e)

Fig. 8. SEM analysis of particles through gasifier-filters (×300) (a) Raw ABK coal, (b) Gas cooler inlet, (c) Inlet Pipe for Filters, (d) Metal Filter Surface and (e) Filter Hopper.

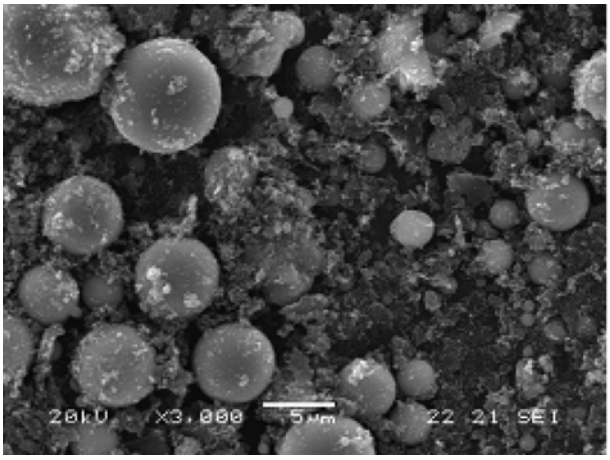


Fig. 9. SEM analysis on fines captured at inlet pipe for filters (×3,000).

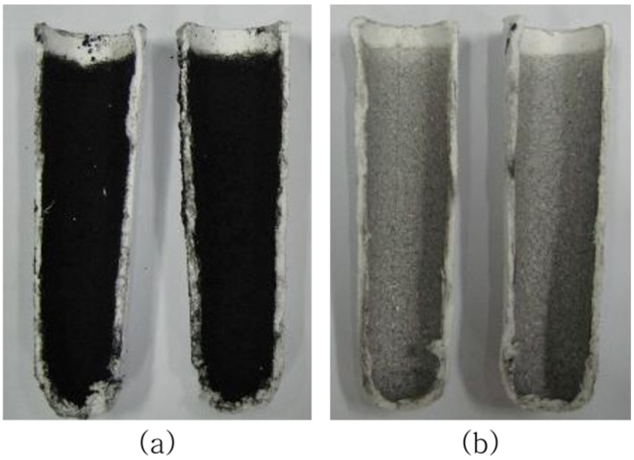


Fig. 10. Fines (a) before metal filters and (b) after metal filters.

particles. These spheric particles appear to be cenospheres that occur during the rapid quenching in temperature of inorganic components that had been melted at high temperatures in the gasifier. Spheric particles shown in Fig. 8(c) were enlarged 10 times to 3,000 magnification and the result is illustrated in Fig. 9. Spherical fines of few micron sizes shown in Fig. 9 appear to the reason for the bimodal peaks in Fig. 7.

The captured fines at the filter hopper should be recycled into the gasifier through the first or second stage nozzles. According to the size distribution and SEM picture as shown in Figs. 7 and 8, recycling with the same injecting facility might not be sufficient since the particles have bimodal distribution with much smaller sizes. In addition, recycled fines contain lower carbon than the raw coal, which suggests the fines might have a lighter density. More care should be given in the details in transporting the captured fines back into the gasifier. A preliminary test on the transporting of captured gasification fines obtained from another coal demonstrated that the same feeding facility for the raw coal was not applicable to the gasification fines. If the feeding pipe size is big enough to prevent any blockage by the gasification fines, the application of the identical feeding facility as raw coal would not cause any operational problem. But, in a small pilot plant of small feeding pipe sizes, differences in surface characteristics and particle density definitely cause the intermittent blockage of pipes.

Table 4. XRF analysis on fines captured at different locations

Sampling location	Raw pulverized coal	Filter hopper	Slag
SiO_2	41.55	45.43	55.79
Al_2O_3	20.24	19.38	16.32
TiO_2	0.72	0.679	0.656
P_2O_5	0.31	0.354	0.18
Fe_2O_3	11.61	12.82	12.51
CaO	10.11	10.31	7.88
MgO	2.73	2.41	2.2
Na_2O	0.6	0.812	0.742
K_2O	1.69	1.69	1.51
SO_3	9.89	5.46	0.1
Cr_2O_3	0.02	0.057	1.19
MnO	0.13	0.139	0.114
CuO	0.04	0.02	0.008
SrO	0.05	0.113	-
BaO	0.19	0.192	0.156
ZnO	0.03	0.033	0.106
Cl	0.02	0.014	-
CoO	0.01	0.016	0.015
ZrO_2	0.01	0.011	0.33
Y_2O_3	-	0.006	-
NiO	0.01	0.022	0.015
V_2O_5	0.03	0.028	0.026
MoO_3	-	-	-

Table 4 shows the XRF analysis results on the fines captured at different locations. Components of low volatile temperature such as SO_3 do not exist much in slags, whereas components like ZnO and ZrO_2 are concentrated in slags. In terms of heavy metal components in slags, the two-stage gasification appears to produce a similar pattern of slags as in the one-stage gasifier.

Two-stage gasification showed similar performance in metal fil-

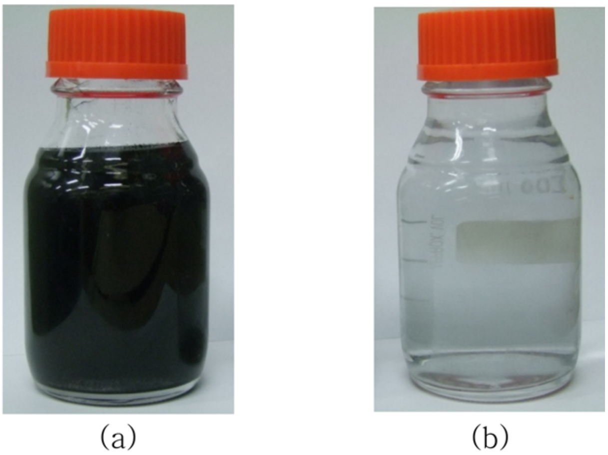


Fig. 11. Scrubbed water (a) before metal filters and (b) after metal filters.

ters and the subsequent scrubber. Fig. 10 shows the pictures of fines captured in the thimbles that were used in the measurement of fines concentrations. Left picture is for the fines that were included in the uncleaned syngas before entering the metal filters. The fines concentration in this case was 2,808 mg/m^3. Right side picture is for the cleaned gas after the particulates removal by metal filters. Fines concentration in the cleaned gas was 15 mg/m^3, which means the 99.47% of removal efficiency.

Fig. 11 shows the pictures for the scrubbed water before and after the metal filtering system, which clearly demonstrates the effect of particulates removal. The scrubbed water before metal filter was obtained by bypassing the uncleaned syngas from metal filters to the scrubber. Scrubbed water contains almost no particulates, but it contains a high concentration of HCN, H_2S, and other trace gases. The fouled smell from the scrubber water after being stored for several hours at room temperature succinctly indicates that sulfur-containing trace gases exist in the scrubber water.

CONCLUSIONS

A one-stage coal gasifier of dry-feeding type was modified to accommodate the two-stage gasification. As a test to verify the operability of a two-stage gasifier, the study focused on the temperature variation with adding second stage feeding nozzles as well as the characteristics of captured fines that would recycle into the gasifier.

When operated as a two-stage gasifier, the temperature at the second stage dropped about 180 °C to 1,200 °C, while the gasifier temperature at the main reaction zone increased more than 150 °C to the 1,350-1,360 °C level. When additional coal was supplied to the second stage of the gasifier, endothermic reactions resulted in lower temperature, which confirms the performance of the second stage as a reduction area. Additional 25% increase of coal feeding amount to the second stage of the gasifier yielded the carbon conversion loss of few tenths of one percent, suggesting that the 10-20% increase in coal feeding to the second stage might not cause much loss in carbon conversion. However, when the feeding rate to the second stage reduction section is increased to the 40-50% level, the tested two-stage gasifier needs to recycle the captured fines for the higher carbon conversion. All in all, the two-stage gasification appears to exhibit a beneficial effect in increasing the cold gas efficiency for the certain operating range.

Slag size and inner structure shown in the two-stage gasification test showed the similar result as in the one-stage gasification. In terms of heavy metal components in slags, the two-stage gasification also appears to produce a similar pattern of slags as in the one-stage gasifier. Similar performance was observed in metal filters and the subsequent scrubber by the two-stage gasification when compared with the one-stage gasification.

Compared with the earlier report for the identical pilot gasifier of one-stage gasification, the relative peak height of the captured fines at 0.1-1 μm range to the 7-30 μm range was about three times higher in the two-stage gasification test of this study, and it appears that the two-stage gasification had an impact on the increased frequency in the 0.1-1 μm size of fines.

SEM pictures on the fines exhibit small spheric particles, and these spheric particles appear to be cenospheres that occur during the rapid quenching in temperature.

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