

The comparison study on the operating condition of gasification power plant with various feedstocks

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Abstract—Gasification technology, which converts fossil fuels into either combustible gas or synthesis gas (syngas) for subsequent utilization, offers the potential of both clean power and chemicals. Especially, IGCC is recognized as next power generation technology which can replace conventional coal power plants in the near future. It produces not only power but also chemical energy sources such as H₂, DME and other chemicals with simultaneous reduction of CO₂. This study is focused on the determination of operating conditions for a 300 MW scale IGCC plant with various feedstocks through ASPEN plus simulator. The input materials of gasification are chosen as 4 representative cases of pulverized dry coal (Illinois#6), coal water slurry, bunker-C and naphtha. The gasifier model reflects on the reactivity among the components of syngas in the gasification process through the comparison of syngas composition from a real gasifier. For evaluating the performance of a gasification plant from developed models, simulation results were compared with a real commercial plant through approximation of relative error between real operating data and simulation results. The results were then checked for operating characteristics of each unit process such as gasification, ash removal, acid gas (CO₂, H₂S) removal and power islands. To evaluate the performance of the developed model, evaluated parameters are chosen as cold gas efficiency and carbon conversion for the gasifier, power output and efficiency of combined cycle. According to simulation results, pulverized dry coal which has 40.93% of plant net efficiency has relatively superiority over the other cases such as 33.45% of coal water slurry, 35.43% of bunker-C and 30.81% of naphtha for generating power in the range of equivalent 300 MW.

Key words: Gasification, Feedstock, Process Simulation, ASPEN Plus

INTRODUCTION

Much research and development for renewable energy technologies is being performed with the recognition of energy security, considering the high price (over \$140/bbl, based on June, 2008) of crude oil and the crisis of local natural disasters by climate change. Alternative technologies which consider clean and low fuel cost are required to be developed. However, renewable energy technologies cannot provide large amounts of capacity of required electricity in the power generating sector. Moreover, the earth's climate is gradually changing, such as an increase of 380 ppmv of atmospheric CO₂ concentration until 2004.

Gasification technology such as IGCC (Integrated gasification combined cycle) can not only satisfy future energy demand but also provide environmentally acceptable options among the candidate power technologies. In 2007 worldwide the gasification capacity grew to 56 Giga-watts thermal (GW_{th}) of synthesis gas output at 144 operating gasification plants. The technology has many advantages such as (1) clean utilization of fossil fuel without air pollutant emissions (SO_x, NO_x, and particle material) during power generation, (2) increased competition in plant efficiency with comparable conventional power technology, (3) flexible application of feedstock (coal, petcoke, heavy residue oil and biomass) and various combinations of different products, and (4) the opportunity to open new markets for hydrogen derived from fossil fuel. The synthesis gas (syngas) is the initial product for an operating gasification plant. The syngas

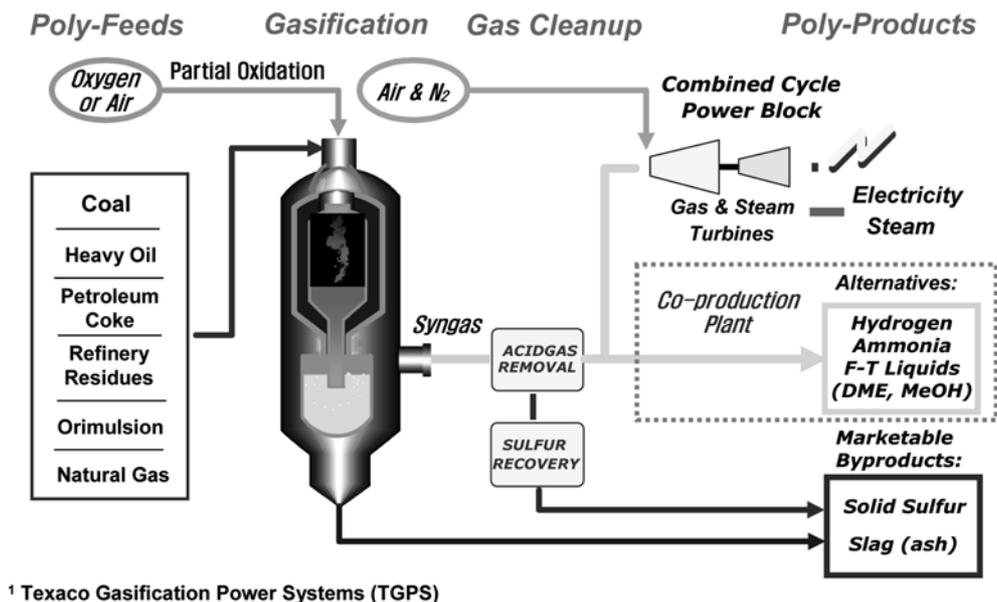
is able to generate marketable products such as chemicals (45%), Fischer-Tropsch liquids (28%), power (19%) and gaseous fuel (8%) in the overall syngas product distribution in the 2007 survey of the international gasification council. Gasification facilities consume a variety of carbon-based feedstocks, including coal, petroleum, petcoke and biomass. From the 2007 survey, coal has increased its leading position as the predominant gasifier feedstock, now accounting for 55% of syngas capacity generated from all feedstocks, compared to 49% in 2004. Petroleum now provides 33% of feedstocks, with the remaining 12% coming from petcoke, natural gas and biomass [1].

A schematic diagram that describes the application range of the gasification technology is illustrated in Fig. 1. The reason for choosing 300 MW capacity for the present investigation is that IGCC not only can generate minimum capacity of demonstration combined cycle composed of 1×1 of gas turbine and steam turbine but also is planned for construction of a commercial IGCC plant in Korea. Under the condition of generating 300 MW capability of electricity, it indicates the characteristics of a gasification power plant by supplying various feedstocks such as pulverized dry coal (PDC), coal water slurry (CWS), bunker-C (BC) and naphtha (NP). This study is focused on the determination of operating characteristics of a 300 MW scale IGCC plant which is applied various feedstocks through ASPEN plus.

SIMULATION METHOD

To determine the characteristics of gasification power plant dependent on various feedstock, a base model of an IGCC plant was de-

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1 Texaco Gasification Power Systems (TGPS)

Fig. 1. Application range of gasification technology.

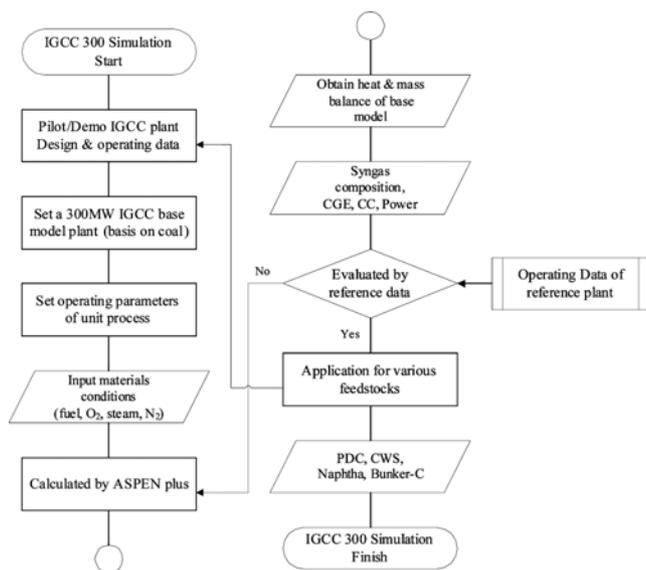


Fig. 2. Flow diagram of simulation procedure for base model of IGCC plant.

veloped with design and operating parameters of 300 MW scale gasification power plant by using ASPEN plus. The constructed base model was composed of fuel preparation, gasification, ash removal, acid gas removal (AGR) process and combined cycle which is compounded with gas and steam turbine. The overall simulation procedure for base model of IGCC plant is shown in Fig. 2. According to the procedure design and operation specifications of IGCC pilot/demo plants are gathered, a base model of a 300 MW IGCC plant is set by the former parameters, heat and mass balances are obtained by ASPEN plus, and the reference plant and base model with minimum relative tolerance are compared. The developed engineering package model is applied to various options of for the IGCC plant considering different feedstocks while investigation is

Table 1. Proximate and ultimate analysis of each feedstock

		Coal (Illinois#6)	Bunker-C	Naphtha
Proximate analysis (wt%)	M	11.2	-	-
	V.M	34.99	-	-
	F.C	44.19	-	-
	Ash	9.7	-	-
Ultimate analysis (wt%)	C	71.72	86.9	84.4
	H	5.06	12.1	15.6
	O	8.08	0.15	<0.01
	N	1.41	0.5	<0.5
	S	2.82	0.3	142 ppm
	Ash	10.91	0.05	20 ppm
^a HHV (kcal/kg)		7,217	10,659	11,432
^b LHV (kcal/kg)		6,951	10,024	10,613

$${}^a\text{HHV (kcal/kg)}=83.43\times\text{C}+281.6\times\text{H}-24.71\times\text{O}-3.61\times\text{N}+24.02\times\text{S}-5.04\times\text{Ash}$$

$${}^b\text{LHV (kcal/kg)}=83.43\times\text{C}+281.6\times\text{H}-24.71\times\text{O}-3.61\times\text{N}+24.02\times\text{S}-5.04\times\text{Ash}-52.53\times\text{H}$$

^{a,b}Heating values are calculated by modified Dulong's equation

carried out with performance variations such as syngas composition, carbon conversion, cold gas efficiency and net power output.

1. Initial Conditions and Assumptions

Input materials for the gasification process were selected to pulverized dry and slurry type coal with Illinois #6 coal, naphtha and bunker-C oil. The basic analysis of feedstocks is presented in Table 1 as a form of ultimate and proximate analysis and heating value. Illinois#6 coal has lower 71.72% carbon and 5.06% hydrogen content than 84.4-86.9% carbon and 12.1-15.6% hydrogen of heavy residue oil (bunker-C, naphtha). On the other hand, Illinois #6 coal has higher content of 8.08% oxygen and 10.91% ash than ~0.15% oxygen and ~0.05% ash of heavy residue oil. Both higher heating values (HHV) and lower heating value (LHV) of feedstock are cal-

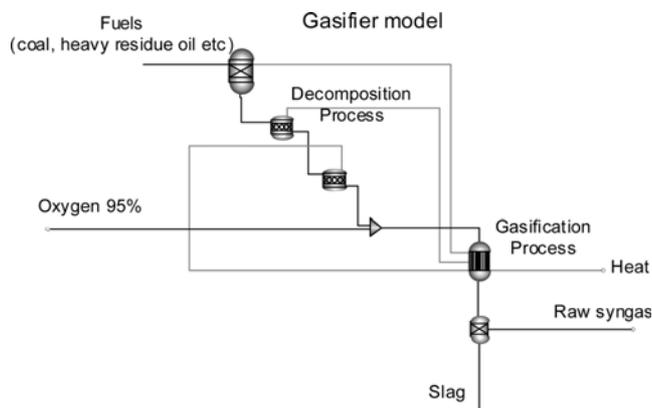
Table 2. Input condition of each feedstock

Flow rate (tons/hr)	Illinois#6 PDC	Illinois#6 CWS	Bunker-C	Naphtha
Fuel	87.5	111.1	65.9	61.5
Oxygen	75.1	94.1	74.5	69.5
Nitrogen	6.65	-	-	-
Water (steam)	-(2.6)	41.6 (-)	-(30.2)	-(30.1)
Air	900	900	1,390	1,390
Diluents N ₂	500	500	253.6	253.6
O ₂ /Fuel	0.86	0.85	1.13	1.13
(H ₂ O+O ₂)/Fuel	0.89	1.22	1.59	1.62

culated by modified Dulong's equation based on the ultimate analysis. The following data were utilized in the simulation study for gasification power plant. At first the IGCC power plant modeled in this study is limited to gasification of pulverized dry coal feeding type. For the 300 MW electricity power in the model, flow rates of fuels and utilities are equivalently calculated and considered in the base model of the IGCC plant for each case. The input conditions for each fuels and utilities are presented in Table 2. It is assumed that the supplied gases such as O₂ and N₂ can be produced from air separation unit (ASU). At that time those gases are supplied to each process such as gasifier (oxidant) and gas turbine combustor (diluents N₂, compressed air) by pipeline, having 95% purity individually. Detailed simulation of ASU plant is excluded from the scope of the present investigation.

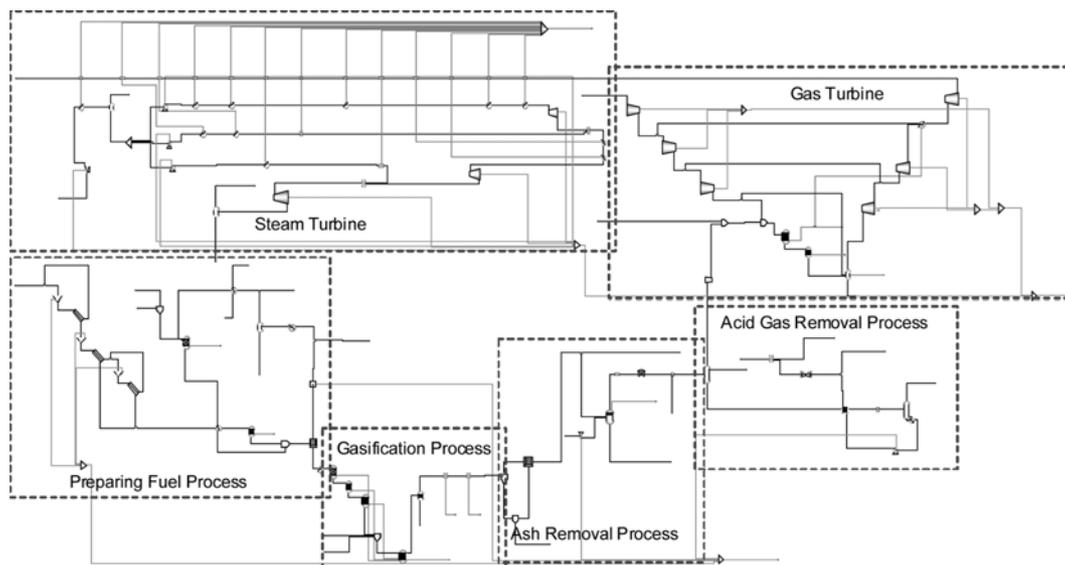
2. Simulation of Unit Process

After the gasification process is simulated for each case of different feedstock input, simulation results are verified by comparing with reference data. A developed model of IGCC power plant is representatively composed of fuel preparation, gasification, ash removal, acid gas removal and combined cycle with gas turbine and steam turbine. The overall gasification plant model made by ASPEN plus is indicated in Fig. 3 [2]. For considering each gasification plant

**Fig. 4. Simulation model of gasifier with ASPEN plus.**

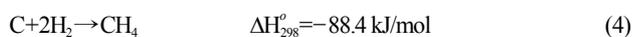
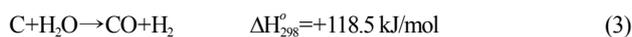
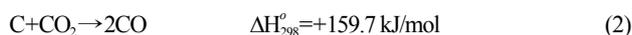
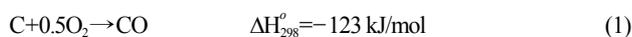
dependent on feedstock, the preparing fuel process is only changed and others are applied at the same. Preparing fuel process consists of coal pulverizing, drying and transporting system with nitrogen gas to the section of coal gasification. After being pulverized by 74 μm of average particle size, the pulverized coal is dried at 95 °C with nitrogen gas and transported to the gasifier by pneumatic transport. For heavy residue oil, fuel preparation involves fuel mixing with steam and supplied system appropriated at liquid phase. The temperature and pressure condition is chosen to mimic actual operating plants worldwide, such as for pulverized dry coal (PDC) type gasifier as 28 kg/cm², 1,420 °C and coal water slurry (CWS) type gasifier as 43 kg/cm², 1,370 °C, respectively.

The gasifier model is divided into four sectors such as decomposition, gasification, soot and slag generation; its process flow diagram is shown in Fig. 4. The gasification model is made of the thermal decomposition process which changes organic materials such as H₂, N₂, O₂, C (carbon), S (sulfur) and ash from solid coal particles. This step occurs in the lower region reactor only, and the RYield (yield reactor block in ASPEN plus) is used to model by specifying the yield distribution according to the coal ultimate anal-

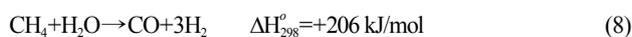
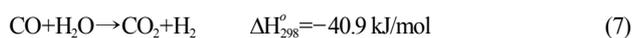
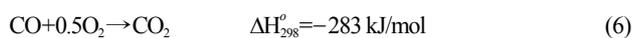
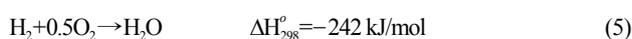
**Fig. 3. ASPEN plus model of 300 MW coal gasification power plant.**

ysis from Table 1. The gasification process proceeds to partial combustion of char particles and organic materials. Then byproducts such as unburned carbon, ash and slag (if gasifier temperature is operated over ash fusion temperature) are generated by passing through decomposition and gasification at the gasifier. These steps are individually described by soot and slag generation, and RStoic (stoichiometric reactor block in ASPEN plus) is used to model in gasifier model.

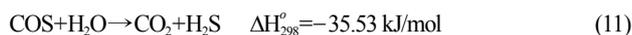
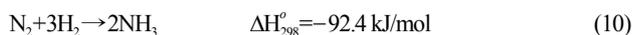
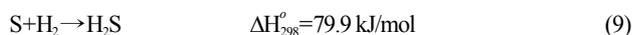
Actual gasification mechanism complexes with various reactions in a real gasification process; however, gasification reactions are simplified to 11 major equations in the present model. Those reaction equations are summarized from (1) to (11) [3]. Reactions (1)-(4) are gasification process of char particles in which CO, H₂ and CH₄ are produced. Reaction (1) is partial combustion of C with exothermic, and the generated heat is supplied to the endothermic reaction (2) of the Boudouard reaction and reaction (3) of heterogeneous shift reaction. Reaction (4) as hydro gasification reaction does not reach equilibrium, because this reaction is dependent on volatile matter of feedstock. The reaction rates of (2)-(4) are known to be slower than that of reaction (1) [4,5].



Reactions of (5)-(8) are gas phase reactions generated from gasification of char particles. Those reactions are, respectively, combustion reaction of combustible gases, water gas shift reaction and methanation reaction.



The following reactions (9)-(10) are, respectively, between hydrogen and organic materials such as sulfur and nitrogen, H₂S and NH₃ are generated. Reaction of (11) produces CO₂ and H₂S between carbonyl sulfide (COS) and H₂O.



The aforementioned 11 reactions are calculated by approaching minimization of Gibbs free energy in the RGibbs block of ASPEN plus. A gasifier model made by this block is also calculated to approach equilibrium state between reactants and products; it is limited to approach syngas composition approximately between simulation model and real gasifier. This is because the actual gasification process cannot approach equilibrium by short residence time of fed feedstock. When O₂ is rare, chars are gasified by the combined chemistry of CO₂, H₂O, CO and H₂. Differences in char reactivity are thought to be even more important in gasification than in oxidation, because the reaction times are so slow that the gasification agents (O₂, steam) can penetrate deeper into the internal pore structure of

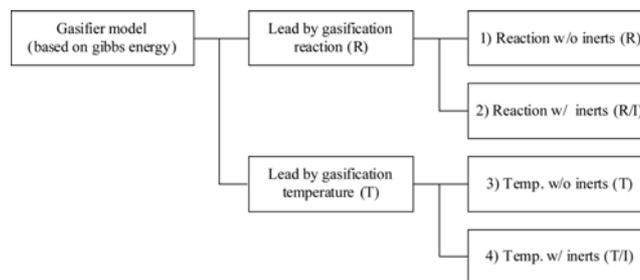


Fig. 5. Evaluation procedure of 4 simulation options for the gasifier model based on RGibbs block.

chars. A more significant difference is that even though steam is injected or raised from water in slurry, the concentrations of the gasification agents are mostly determined by chemistry in the gas phase that partially oxidizes and reforms the primary volatile [6]. So it is assumed that major operating variables are governing individually the gasification reaction and operating temperature with constant pressure at the gasifier block.

For reflecting reactivity of reactants inner gasifier, it is applied inert effect in Rgibbs block for gasifier model. The block has an option which can reflect the inert rate of reactants under restricted reactions. Those methods are indicated in Fig. 5, divided into four cases by reactions (R), temperature (T), reaction with inert effect (R/I), and temperature with inert (T/I) of gasification process. The actual changes of syngas composition with variation of operating pressure are almost negligible for the gasification process under high temperature (over 1,000 °C) [7]. In other words, effective factors that are considered are whether the gasifier model made by RGibbs block in ASPEN plus is limited by reactions inner gasifier or gasifier temperature for approaching syngas composition of an actual IGCC plant. For describing the degree of participation between char and syngas components inner gasifier, the inert fraction (I) of each component (such as carbon, sulfur, nitrogen and CO, H₂O etc) is specified at the gasifier model. Through the simulation method being used for inert effects, the gasifier model can be close to a real gasifier.

With passing through cyclone and metal filter by turns, fly-ash on the inside syngas is removed to near removal efficiency of 99%. Then syngas removed ash leads to acid gas removal (AGR) process, which can capture acid gases (CO₂, H₂S) by absorbent as 20 wt% MEA solution; the MEA process is operated in the range of 40-110 °C. The absorbent is recycled between absorber and regenerator column; absorbent has an acid gas removal efficiency of 95-99%.

The gas turbine model is referenced by PG7241[FA] made by GE; the specifications are indicated in Table 3 [8]. This model is individually composed of compressor, combustor, NO_x-former and expander. Both physical and chemical phenomena of the combustor are largely divided by combustion section as a chemical reaction

Table 3. Specification of reference model of gas turbine

Parameters	PG7241 [FA]	GT model
Firing temp (°C)	1327	1320
Pressure ratio	15.5 : 1	15.5 : 1
Generating power (MW)	171.7	188.4

between syngas and compressed air, and diluents section for controlling turbine inlet temperature with mixing high thermal exhaust gas and compressed cooled air [9,10]. CO₂ free syngas passing through AGR is compressed to 15-16 kg/cm², and then injected to gas turbine combustor with high pressure of air and N₂ gas. The power of IGCC plant is affected by requirements of compressed air and diluents N₂ injected to gas turbine. Those mass flow rates of air and N₂ gas are shown in Table 2. After being combusted near 1,260 °C at gas turbine cycle, power is generated by high thermal and pressurized combustion gas. Finally, exhaust gas including high thermal passes through the heat recovery steam generator (HRSG), and waste heat of exhaust gas is recovered and used as heat source at steam turbine cycle. The steam turbine is composed of 3 stage compressors operating at high pressure (98 kg/cm²), intermediate pressure (20 kg/cm²) and low pressure (4 kg/cm²) steam with inlet temperature as 540/540/325 °C and outlet temperature as 340/200/200 °C in order HP/IP/LP.

RESULTS AND DISCUSSION

An IGCC base model is developed dividing dry and wet (slurry) feeding type near to each reference IGCC plant [11,12]. Simulation

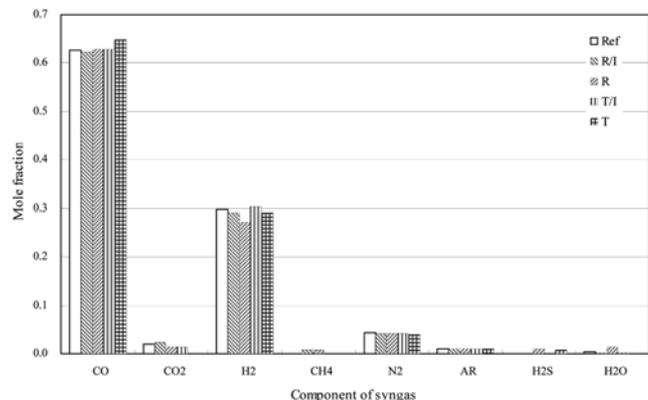


Fig. 6. Evaluation of results of pulverized dry Illinois#6 coal by 4 simulation methods for the gasifier (at 28 kg/cm², 1,420 °C).

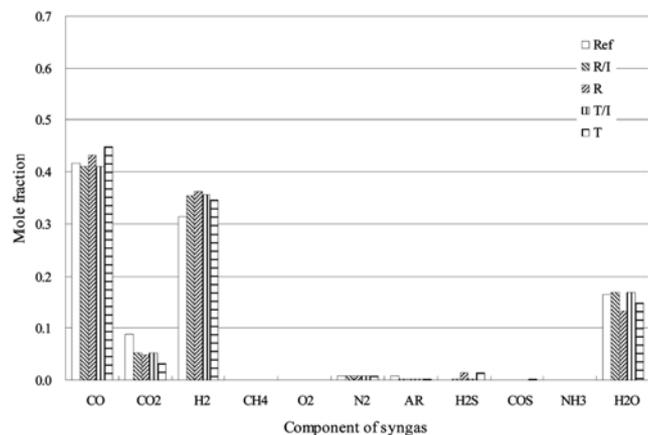


Fig. 7. Evaluation of results of coal water slurry of Illinois#6 coal by 4 simulation methods for the gasifier (at 43 kg/cm², 1,370 °C).

results are obtained from 4 cases of IGCC base models, and those results are evaluated with reference data of the demo plant (see Figs. 6-7). The R/I method applied in the case of PDC as dry feeding type has the least relative errors of major syngas components (0.74% CO, 11.15% CO₂, 2.18% H₂, 2.84% N₂, and 1.78% H₂O) based on reference data among the 4 simulation methods. The T/I method can similarly approach the reference data in the case of CWS as wet feeding type. So a gasifier is simulated of both PDC by R/I and CWS model by T/I method. This method is one way to describe not equilibrium but actual reaction among the reactants inner gasifier. So inert fraction values for each case are investigated. Inert fractions of each component are to 6% carbon, 15.6% H₂O, 99.5% sulfur, and 99.8% N₂ in PDC case. The inert fractions of CWS model are to 7% carbon, 41.2% H₂O, 86% sulfur, and 95% N₂. The syngas from CWS fed gasifier contains more CO₂ and H₂ and less CO than that from the PDC gasifier because an excess of steam is consumed in the reaction (7). According to Fig. 7, CO₂ and H₂ components show a contrary difference with reference tendency (less CO₂ and more H₂ based on reference composition); this divergence is thought to occur because of a water gas shift reaction with surplus fed water, different from the PDC case. The higher O₂/coal ratio used for the CWS gasifier suggests that a larger part of the carbon in the coal was converted to CO₂ than that in the PDC gasifier. In addition, the higher temperature employed in the latter gasifier slows the oxidation of CO to CO₂. The difference in CO₂ content is responsible for the significant difference between the composition of PDC and CWS gasifier [13].

After evaluating CWS of the IGCC base model, we simulated bunker-C (BC) and naphtha (NP) cases based on CWS model. Both BC and NP models also obtained a syngas composition like Fig. 8 under similar input condition of the reference data. Fig. 8 indicates that the simulated syngas composition has a similar tendency with reference data for each case. Syngas compositions with different feedstock such as PDC, CWS, BC and NP are respectively monitored before and after absorber at the AGR unit, and those raw and washed syngas compositions are presented in Table 4. CO₂ component is produced at the range of 2.3-4.9 mol% in the overall syngas for the 4

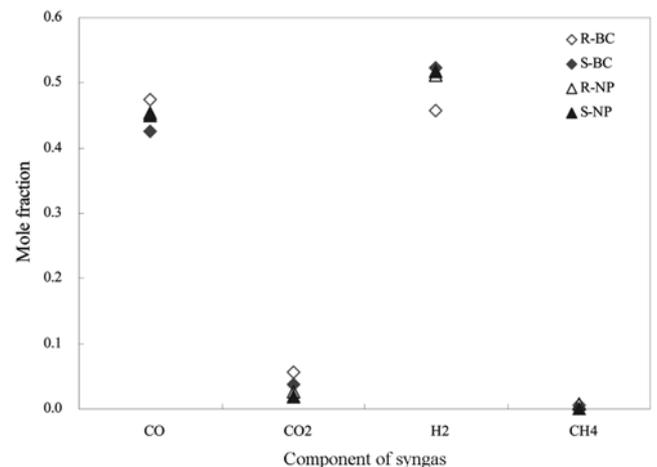
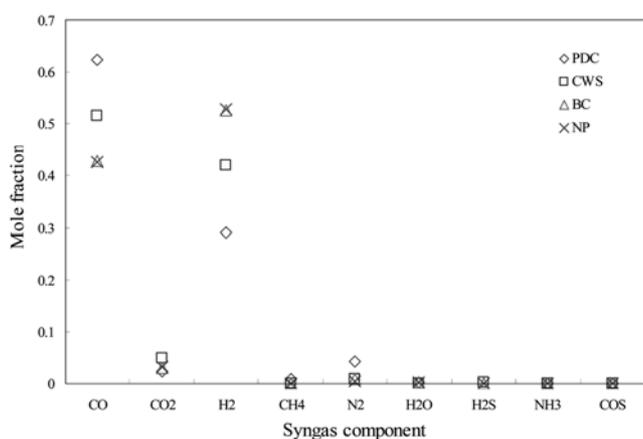


Fig. 8. Evaluation of results of bunker-c and naphtha at 43 kg/cm², 1,370 °C (Reference data as R-BC, R-NP from Texaco operation data [5]).

Table 4. Syngas compositions depending on feedstock before and after absorber at the AGR unit

Component (mol%)	Illinois#6 PDC		Illinois#6 CWS		Bunker-C		Naphtha	
	Raw	Washed	Raw	Washed	Raw	Washed	Raw	Washed
CO	62.4	63.5	51.6	51.3	42.8	43.1	42.6	42.8
CO ₂	2.3	11 ppm	4.9	41 ppm	3.0	trace	3.2	trace
H ₂	29.1	30.3	42.1	47.5	52.7	55.6	52.9	55.9
CH ₄	0.9	0.7	293 ppm	43 ppm	164 ppm	121 ppm	151 ppm	108 ppm
N ₂	4.2	4.3	0.8	0.9	0.8	0.8	0.5	0.5
H ₂ O	0.2	0.2	22 ppm	0.1	0.2	0.1	0.2	0.1
H ₂ S	trace	trace	0.2	trace	120 ppm	15 ppm	120 ppm	9 ppm
NH ₃	120 ppm	trace	24 ppm	trace	26 ppm	trace	20 ppm	trace
COS	51 ppm	62 ppb	74 ppm	trace	4 ppm	trace	4 ppm	trace
Flow rate (kmol/hr)	7,493.1	7,177.5	6,632.0	5,877.3	9,913.4	9,408.4	9,264.5	8,760.8

**Fig. 9. Syngas compositions depending on the 4 feedstocks (PDC, CWS, BC and NP) at the latter of gasifier.**

cases. Especially, CWS including H₂O contents artificially shows 4.9 mol% CO₂ higher than the other cases. Comparing syngas composition of PDC with CWS, the H₂O supplement in reaction (7) has not only a role to increase H₂ but also CO₂ contents in CWS. Most acid gases such as CO₂, H₂S and COS are removed near 99.9% of removal efficiency. For easily comparing gasification characteristics dependent on feedstocks, the syngas compositions dependent on 4 cases of feedstock are totally shown in Fig. 9. According to Fig. 9, PDC shows 63.5 mol% CO richer than 30.3 mol% H₂, while CWS, BC and NP like as liquid phase feedstock shows 47-56 mol% H₂ and 43-52 mol% CO, similarly.

To indicate the gasification performance of each case, cold gas efficiency (CGE) and carbon conversion (CC) are defined as Eq. (12) and Eq. (15) at the point of the gasifier [7]. For calculating CGE of gasifier, higher heating values (HHV) used at Eq. (12) are, respectively, calculated by Eqs. (13)-(14). Product gases are limited by combustible components ($i=CO, H_2, CH_4$) in Eq. (14).

$$CGE(\%) = \frac{HHV_{pg}[\text{kcal}]}{HHV_f[\text{kcal}]} \times 100 \quad (12)$$

$$HHV_f = HV_f \times 10^{-3} \quad (13)$$

$$HHV_{pg} = \sum_i (C_i \times HV_i) \times F_i \quad (14)$$

The carbon conversion of Eq. (15) is calculated from total carbon quantity of product gas defined as Eq. (17) divided by total carbon quantity of input feedstock defined as Eq. (16).

$$CC(\%) = \frac{C_{b_{pg}}[\text{kmol/h}]}{C_{b_f}[\text{kmol/h}]} \times 100 \quad (15)$$

$$C_{b_f} = 0.833f_s U_c \quad (16)$$

$$C_{b_{pg}} = \sum_i C_i \times F_i \quad (17)$$

$$\eta_{net} = \frac{P_{net}[\text{MW}]}{HHV_f[\text{kcal}]} = 8.5986 \times 10^4 P_{net} HV_f^{-1} f_s^{-1} \quad (18)$$

The results obtained from the IGCC base model are calculated by gasification performance following Eq. (12), Eq. (15) and Eq. (18) as plant net efficiency (η_{net}) based on HHV. The net power of Eq. (18) is obtained from simulation of the IGCC base model. Gasification performances by the variety of feedstock are indicated in Fig. 10. When it is simulated for each case, concentration of both O₂ and CO₂ among emission contents is, respectively, controlled in the range of 6-7 mol% of overall exhaust gas. The power outputs of 4 cases are calculated under the following restriction. This restriction is satisfied with the regulation of emission limits through a correction based on 15% of oxygen [14]. According to the results of Fig. 10, if the equivalent 300 MW power output is obtained, CWS is required to have an excess 26.86% of coal demand than PDC. Because CWS includes 35% of H₂O component, CWS (CGE: 54.8%, CC: 95.4%) has lower cold gas efficiency than PDC (CGE: 75.8%, CC: 93.9%). However, H₂O content has a role to decrease the heat value of inner gasifier; it also requires an increase of O₂ requirements for gasification reaction as in Table 2. CGE has a tendency to rise as O₂ ratio fed to gasifier is increased. Besides, it also derives a CO shift reaction; CWS has higher H₂ content than PDC. In the face of plant net efficiency, PDC has 40.93% of the highest efficiency among the 4 cases. Both BC and NP shown similar performances of gasification in Fig. 10.

CONCLUSIONS

Simulation models of a 300 MW scale IGCC plant are developed to predict gasification performance by variety of feedstock. The variety of feedstock is considered by four cases, such as pulverized dry

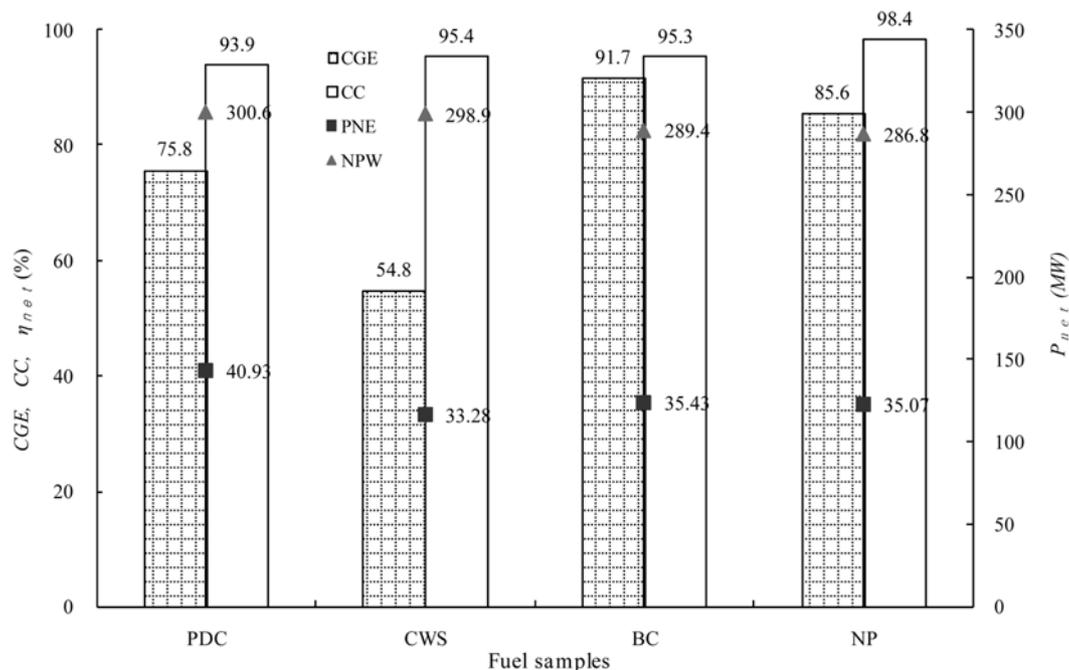


Fig. 10. Gasification performances (CGE, CC, η_{net} , P_{net} power) by the variety of feedstock.

and water slurry type of representative Illinois#6 coal, bunker-C and naphtha. After constructing the IGCC base model for four cases, we compared its gasification performance approaching to the equivalent 300 MW power output. This enabled us to indicate appropriate operating parameters of the unit process for each case. The gasifier model with simulation method considering gasification reactivity between reactants should be suggested to approach to near actual gasifier. IGCC plant models for four cases were verified by operating data from reference plants. Gasification performance, such as cold gas efficiency, carbon conversion, plant net efficiency and net power by developed IGCC base models, was calculated. Pulverized dry coal, bunker-c and naphtha coincide well with reference data of the demo plant, but coal water slurry did not coincide well at the CO_2 and H_2 content of syngas composition. It is estimated that these tolerances occurred by a lack of reference operating parameters and gasification mechanism in the coal water slurry. So future work requires a study of the kinetics of coal water slurry gasification. With this study, one is able to compare gasification plant performance with various feedstocks. In addition it will enable to simulate applications of a gasification plant with poly-feeds and poly-products.

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NOMENCLATURE

BC : bunker-C
 C_i : mole fraction of component i [mol%]
 C_{b_f} : carbon quantity of input fuel [kmol]
 $C_{b_{pg}}$: carbon quantity of product gas [kmol]

CC : carbon conversion [%]
 CGE : cold gas efficiency [%]
 CWS : coal water slurry
 F_t : total flow rate of product gas [kmol/hr]
 f_s : flow rate of input condition for each fuel [tons/hr]
 HV_f : higher heating value of fuel per unit mass [kcal/kg]
 HV_i : higher heating value of component i
 HHV_f : higher heating value of input fuel [kcal]
 HHV_{pg} : higher heating value of product gas [kcal]
 LHV : lower heating value [kcal]
 NP : naphtha
 U_C : weight fraction of carbon content at ultimate analysis [wt%]
 η_{net} : plant net efficiency
 P_{net} : net power [MW]
 PDC : pulverized dry coal

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