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Evaluation on the Performance and the NOx Emission of IGCC Power Plant Integrated with Air Separations Unit

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Abstract *- Thermodynamic simulation method is developed and applied to analyze the performance and the NOx emission characteristics of the IGCC(Integrated Gasification Combined Cycle) power plants coupled with ASU(Air Separation Unit). Simulations on IGCC power plants are made through combining the chemical process models for gasification and gas clean-up and the thermodynamic combined cycle model with NOx prediction capability. With coal or heavy residue oil as feedstock of IGCC, the present study investigates and compares the power output, the overall efficiency and the NOx emission characteristics of various IGCC plants at different ASU integration conditions in order to give the design criteria for efficient and environmental friendly IGCC configuration.*

Keywords *-* **ASU Integration, Air Extraction, Nitrogen Dilution, NOx Emission.**

1. INTRODUCTION

Recently IGCC is being considered as a next generation fossil power plant type in the aspects of higher overall cycle efficiency and superior environmental performances compared with conventional coal-fired power plants, so it could be a very suitable power plant option for meeting worldwide climate change regulations and standards in near future. However, because IGCC shows typically very complicated combination of gasification, gas clean-up, gas turbine, steam cycle and ASU systems with various energy and mass integration schemes affecting the overall performances and the emission characteristics of IGCC[1], it is very difficult for the engineers in power industry to determine the optimum integration condition of the subsystems.

As shown in Fig.1, the fuel of gas turbine combustor of IGCC is derived from coal or even heavy residue oil in refinery process[2]. In general, the heating value of the syngas fuel is about 20-30% of the natural gas. For this reason, the IGCC gas turbine combustor requires 4-5 times fuel consumption of the syngas compared with the natural gas combustor at the same turbine inlet temperature(TIT) condition. Another different feature of IGCC from conventional coal and natural gas power plants can be found in ASU-gas turbine integration scheme. Air is extracted from gas turbine compressor and then is fed to the ASU, which separates air to the oxygen for the oxidizer of coal gasification and the nitrogen for the dilution agent of NOx control in gas turbine combustor. However, because the most of large industrial gas turbines for IGCC application are designed as natural gas firing unit, so the low-Btu gas firing and the ASU integration of the gas turbine of IGCC make the operation of the gas turbine shift toward off-design point and then unstable range such as surge[1].

For this reason, the design concept and the method of ASU-gas turbine integration severely affect both the performance and the emission characteristics of IGCC power plants. However, previous IGCC simulation studies were focused only on the on-design point performance evaluations by using thermo-chemical analyses[3,4,5], so they need to be revised to predict both the off-design effect of gas turbine and the NOx emission of IGCC power at different ASU integration scheme.

Therefore, the present study develops a simulation method of IGCC power plant, which contains the chemical process models of gasification and gas clean-up, and the models for combined cycle with NOx emission prediction capabilities. Furthermore, with the syngas fuel derived from coal or heavy residue oil, the present simulation method investigates the overall cycle efficiency, the power output, the pressure ratio and the NOx emissions of IGCC power plant by varying the ASU integration conditions.

2. IGCC SIMULATION METHOD

Gasification and Gas Clean-up Processes

As shown in the process flow diagram of Fig. 2, the present study employs Shell process as gasification and acid gas removal-Claus-SCOT process combination as desulfurization of raw syngas. Coal or heavy residue oil gasification process under high temperature and pressure is modeled by Gibb's free energy minimization method for the following char and gas-phase reaction equations:

Gasification reaction model:

• Char reactions

$$C(s) + 1/2\ O_2 \leftrightarrow CO\ ,\ C(s) + O_2 \leftrightarrow CO_2\ ,$$
$$C(s) + CO_2 \leftrightarrow 2\ CO\ ,\ C(s) + H_2O \leftrightarrow CO + H_2\ ,$$
$$C(s) + 2H_2 \leftrightarrow CH_4 \qquad (1)$$

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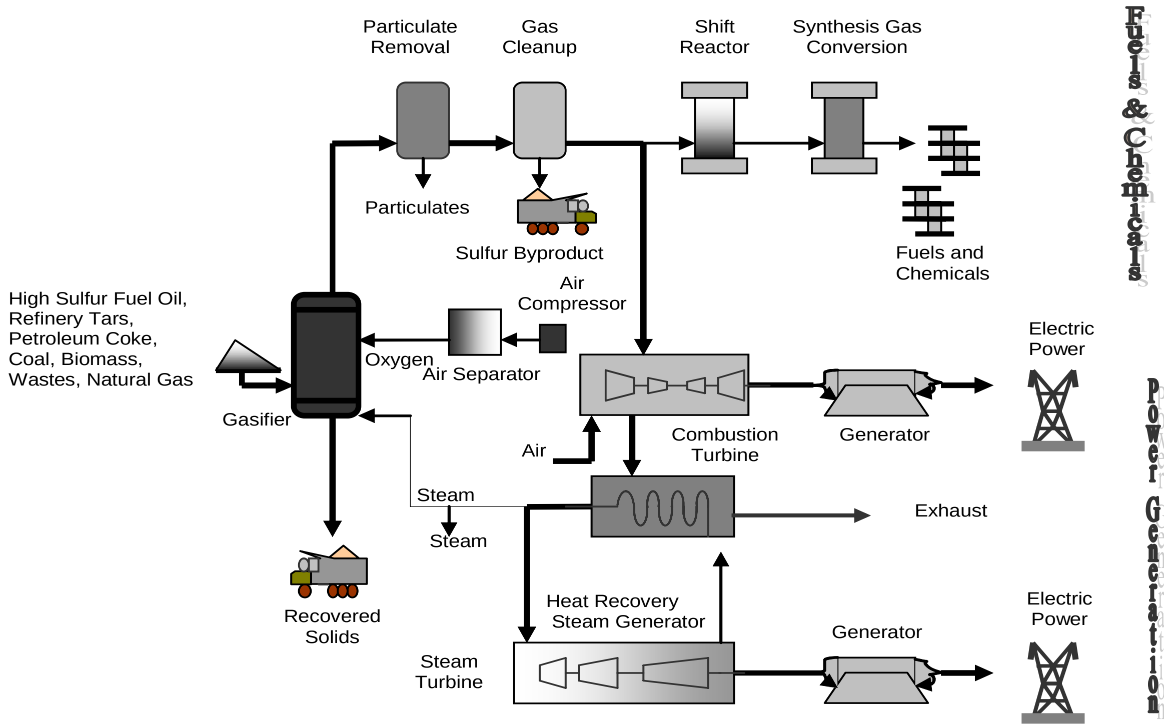

Fig. 1. IGCC integration scheme.

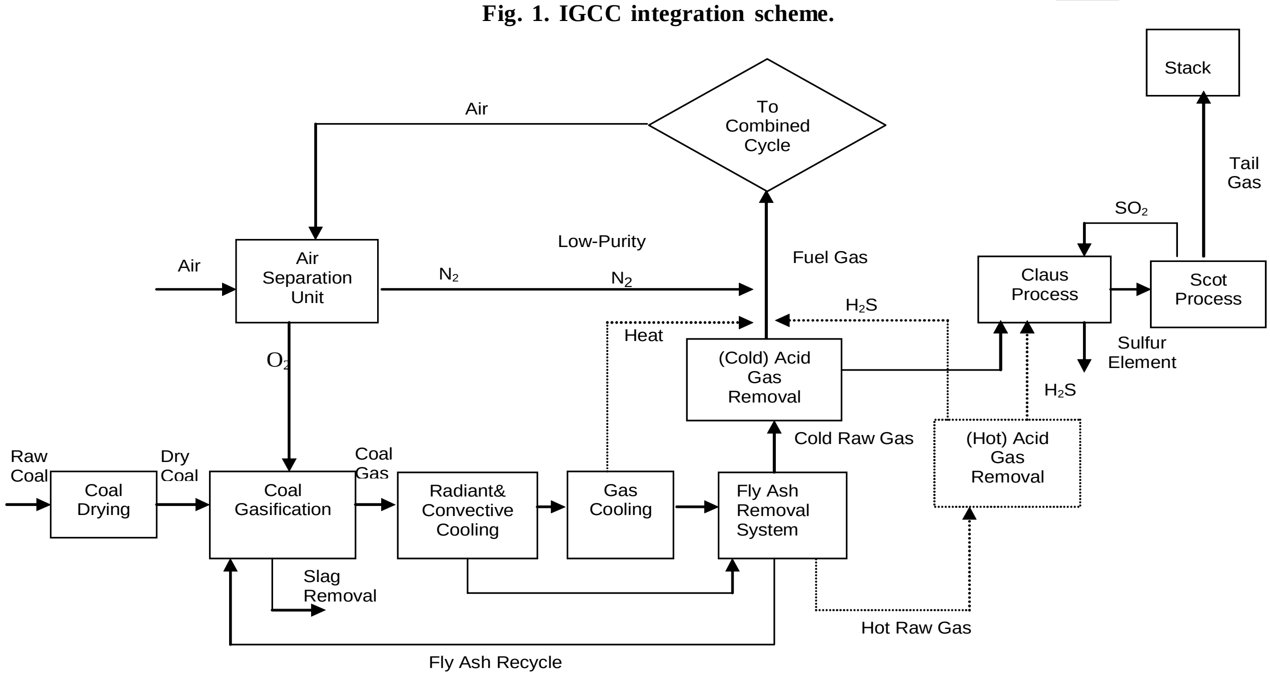

Fig. 2. Process flow of gasification and gas clean-up.

• Gas phase reactions

$$CO + 1/2\,O_2 \leftrightarrow CO_2\,,\ CO + H_2O \leftrightarrow CO_2 + H_2\,,$$
$$N_2 + 3H_2\ \ 2\,NH_3,\ COS + H_2O \leftrightarrow H_2S + CO_2\,,$$
$$S + H_2 \leftrightarrow H_2S \qquad (2)$$

Gas-cleanup reaction model:

• MDEA process

$$H_2S + MDEA \leftrightarrow MDEAH^+ + HS^- \qquad (3)$$

• Claus process

$$H_2S + 3/2\,O_2 \leftrightarrow SO_2 + H_2O,$$
$$COS + 3/2\,O_2 \leftrightarrow SO_2 + CO_2\,,$$
$$2\,H_2S + SO_2 \leftrightarrow 3\,S + 2\,H_2O \qquad (4)$$

•SCOT process

$$COS + H_2O \leftrightarrow H_2S + CO_2\,,$$
$$SO_2 + 3\,H_2 \leftrightarrow H_2S + 2\,H_2O,$$
$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad (5)$$

Here, the details about modeling techniques and kinetic data of the above chemical reactions are well described in the ASPEN Plus user manual[6].

In the present study, Datong bituminous coal or Visbreaker residue is used as feedstock of IGCC, and the characteristics of the syngas derived through gasification and gas clean-up processes are represented in Fig. 3. As shown in Fig. 3, the optimum ratio of O_2 to feedstock can be selected as 1 because of the best carbon conversion and cold gas efficiency at the point. The predicted composition and heating value of the syngas fuel are summarized also in Table 1 and then they are used as the input data for the gas turbine combustor of combined cycle simulation.

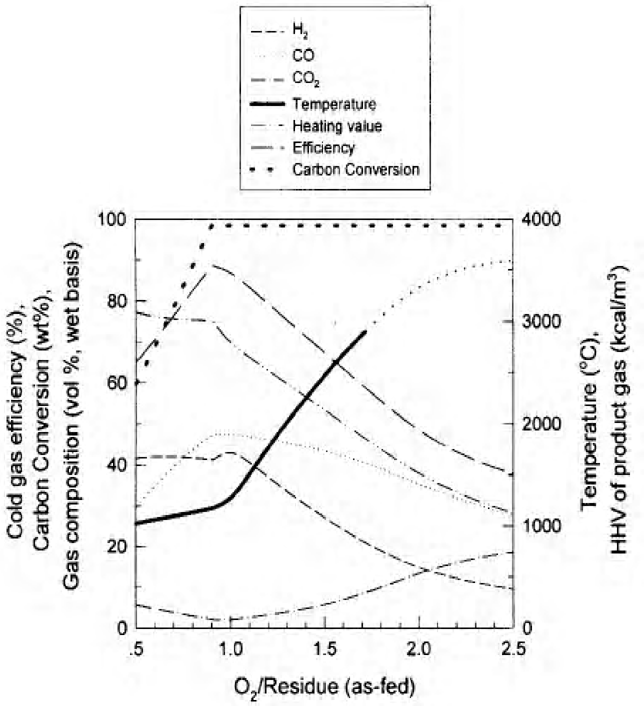

Fig. 3. Characteristics of syngas.

Table1. Syngas fuel conditions

Composition (vol. %)	Visbreaker residue	Datong bituminous
H_2	45.50	29.33
CO	50.28	64.57
CO_2	2.25	0.71
H_2O	0.19	0.14
CH_4	0.50	0.04
N_2	0.40	4.49
Ar	0.88	0.72
LHV(kJ/kg)	15729.8	12358.4

ASU-Gas Turbine Integration

As mentioned before, in IGCC power plant, ASU and gas turbine is integrated through air and nitrogen streams. Fig.4 shows typical air/N_2 integration scheme between ASU and gas turbine. Air is separated into oxygen and nitrogen by the distillation column process of ASU, and the oxygen is used as the oxidizer for coal gasification while nitrogen is being used for the dilution agent of NOx control in gas turbine combustor.

In this air/N_2 integration scheme, because the total air required in ASU can be supplied by gas turbine compressor or/and supplementary compressor, so the air extraction ratio defined as the extracted air(A) to the total ASU air(B) is main design parameter. Nitrogen dilution is also seriously affecting parameter on the performance and the emission of IGCC power plant[1].

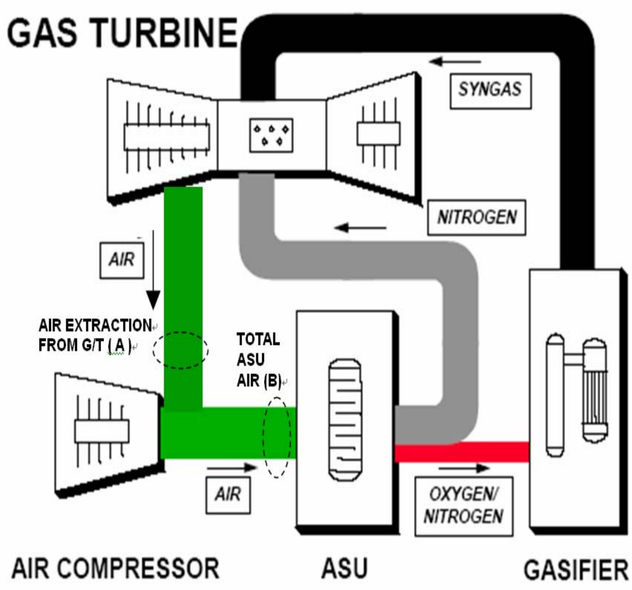

Fig. 4. Air/N_2 Integration between Gas Turbine and ASU.

Combined Cycle

Topping Cycle

As shown in Fig. 5, the combined cycle power block of IGCC is composed of the topping cycle of gas turbine integrated with ASU and the steam bottoming cycle utilizing the waste heat of the gas turbine. The thermodynamic simulation of combined cycle is conducted by using the GateCycle code[7] with user-supplied model for NOx emission prediction. The present study also assumes the ASU as double distillation column type.

For the analysis of the present study, GE's MS7001FA is selected as the gas turbine model of the present IGCC power plant. The MS7001FA is designed originally with natural gas, and its design pressure and TIT(turbine inlet temperature) are 15 °C and 1288 °C respectively[8]. In gas turbine modeling, air compressor is modeled by combining the thermodynamic calculation procedure for air compression and its performance characteristic curve representing relationship between air flow, efficiency and pressure ratio. Combustor model calculates heat and mass balances for three incoming streams of air from compressor, returned nitrogen from ASU and clean syngas fuel through chemical processes. In addition, the present combustor analysis method can predict the NOx emission level by applying the semi-analytical model of Lefebvre[9] expressed as the following equation:

$$NO = \frac{\alpha P^{1.2} \exp(0.009\, T_{pz})}{m_{air,pz} T_{pz} (\Delta P / P)^{0.5}} \text{ [g/kg]} \qquad (6)$$

where $m_{air,pz}$, T_{pz} are the air flow, the temperature at primary combustion zone, and P,ΔP are operating pressure and pressure loss of combustor. It is noted that α is gas turbine-specific constant, so it is tuned by using the MS7001FA's actual test data for NOx emission when burning natural gas[10].

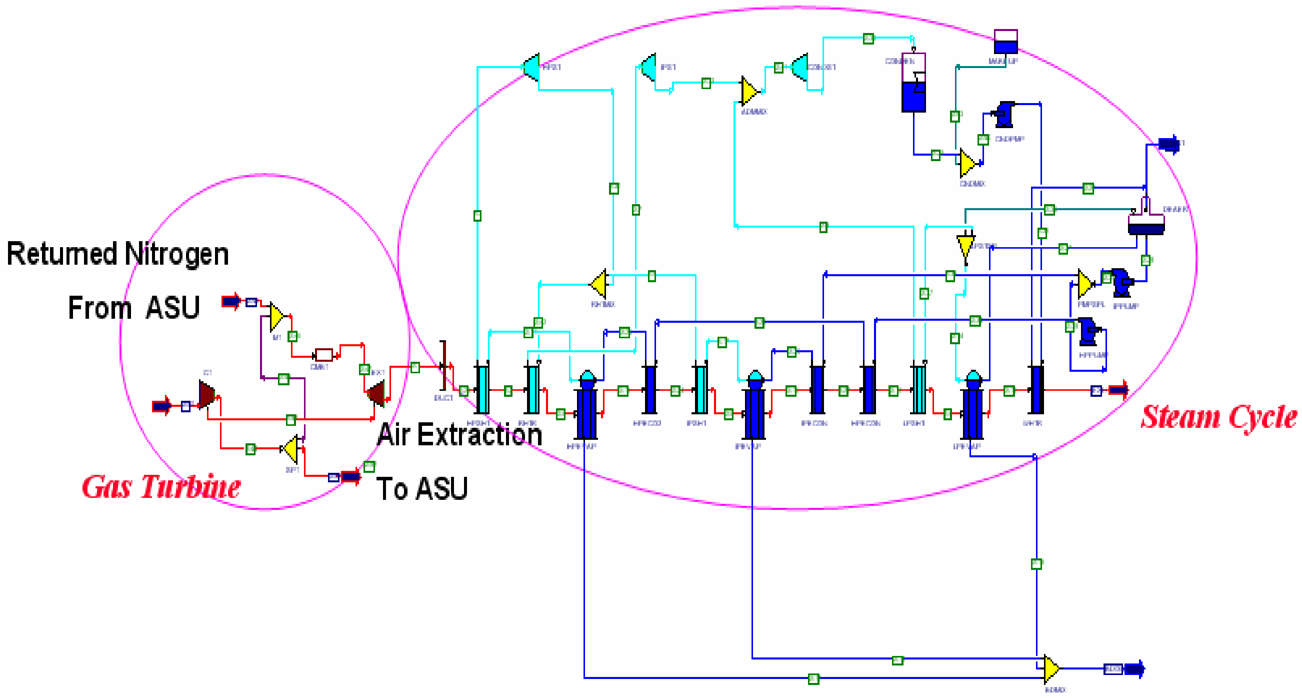

Fig. 5. Combined Cycle Simulation Model.

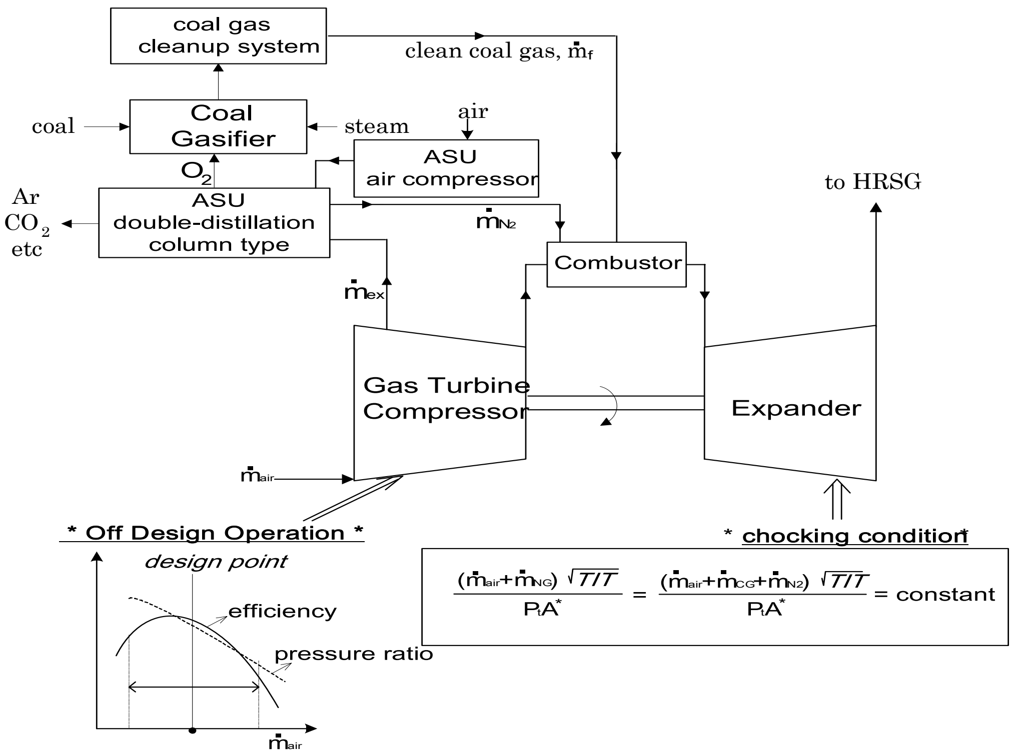

Fig. 6. Schematic Diagram of the Gas Turbine Integrated with ASU.

The expansion process of turbine expander is modeled by stage-by-stage analysis. In the turbine analysis, turbine inlet pressure is computed from choking conditions[11] for natural gas firing and IGCC cases as follows:

$$\frac{(m_{air}+m_{CG}+m_{N2})\sqrt{TIT}}{PA_t}=\frac{(m_{air}+m_{NG})\sqrt{TIT}}{PA_t}=const \tag{7}$$

where P, TIT and A_t mean the inlet pressure, the temperature and the throat area of turbine expander, and m_{air}, m_{N2}, m_{CG} and m_{NG} represent the flow rates of air from compressor to combustor, returned nitrogen from ASU, coal gas and natural gas entering combustor respectively.

When gas turbine burns the syngas and integrates with ASU, the air flow condition of compressor is shifted to off-design point where corresponding pressure ratio and efficiency are determined from the characteristic curve as shown in Fig.6 because generally 4-5 times fuel consumption is required for the syngas than the natural gas and the returned nitrogen from ASU is additionally fed back to IGCC gas turbine combustor. It is noted from the equation (6) that the mass addition effects at expander inlet are generated from ASU integration and then cause the changes in compressor air flow and pressure ratio along the performance curve depicted in Fig.7. The compressor performance curve used in this study is obtained from the generalized maps of the GateCycle library[7].

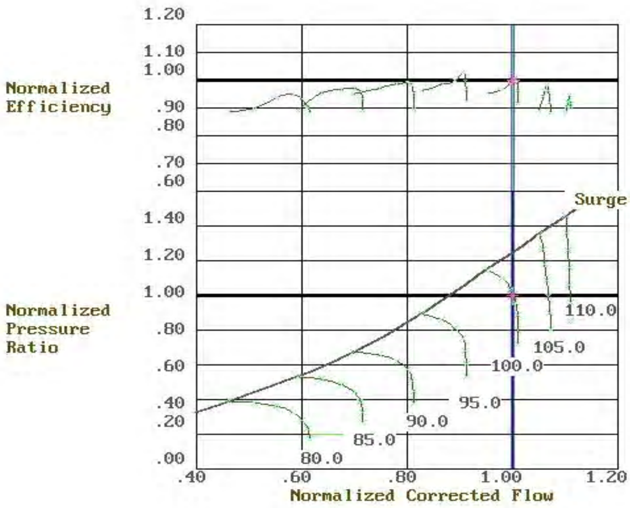

Fig. 7. Generalized Performance Map of Compressor.

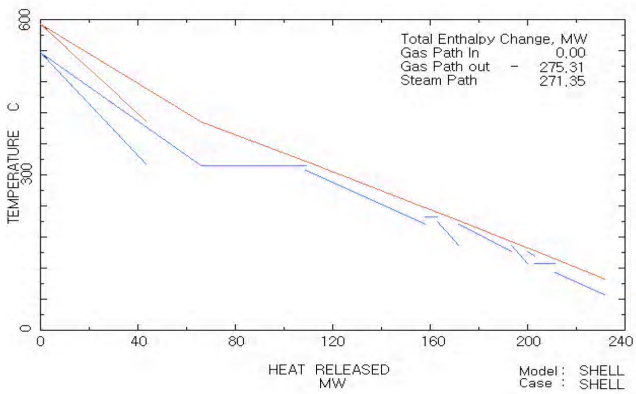

Fig. 8. Temperature Profiles of Flue Gas and Water/Steam.

Bottoming Cycle

Bottoming cycle design has significant impacts on the overall combined cycle performances of IGCC, so the present study reviewed various design parameters such as main steam pressure and temperature, reheat vs. non-reheat steam turbine, single pressure vs. multiple-pressure HRSG, fired or unfired HRSG and flue gas temperature. Finally, the present steam cycle is designed at the main steam conditions of 103 kg/cm^2 and 538 ^{o}C, the stack flue gas temperature above 100^{o}C and is also constructed with the configuration of unfired and triple pressure HRSG with high pressure(HP), intermediate pressure(IP) and low pressure(LP) steam generations. As shown in Fig.5, the heat exchanger arrangement of the present triple pressure HRSG along flue gas path is made as follows:

HP superheater – reheater – HP evaporator – HP economizer#2 – IP superheater – IP evaporator – IP economizer – HP economizer#1 – LP superheater – LP evaporator

Figure 8 also shows the temperature profiles of flue gas and water/steam along the above HRSG arrangement when the MS7001FA gas turbine is used as topping cycle.

3. SIMULATION RESULTS AND DISCUSSIONS

In order to examine the validity of the present simulation method, the predicted performance results by the present method are favorably compared with the actual test results of the Seo-Inchon combined cycle power within the relative error of 5%. In addition, the NOx emission prediction results are also well agreed with the combustor test results of General Electric[10] within the relative error of 10% as shown in Fig.9.

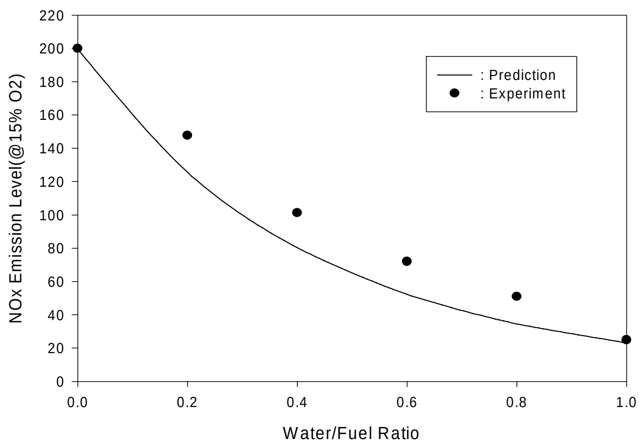

Fig. 9. NOx Emission of MS7001FA Gas Turbine.

Figures 10-11 and Figs. 12-13 show the net power outputs of IGCC power plants with or without nitrogen dilution for gas turbine combustor. Please note that ASU power contains the power consumptions of supplementary air compressor and distillation column process. With the decrease of air extraction ratio, the gas turbine power, the steam turbine power and the ASU are increased for both coal and HRO(heavy residue oil) IGCC cases. This tendency is explained from the fact that less air extraction ratio results in higher air flow rate passing through the gas turbine compressor, in turn giving more turbine work and more waste heat in flue gas. Nitrogen dilution shows the remarkable effect on power enhancement because of the large nitrogen mass addition into turbine expander. Comparing two kinds of IGCC feedstocks, the coal IGCC is superior to the heavy residue oil IGCC in producing net power output.

Figures 14 and 15 show the overall IGCC efficiencies ranging within 49-52% based on LHV. The best IGCC efficiency is achieved at 20% air extraction in the case without nitrogen dilution, but at 40-60% air extraction in the case with nitrogen dilution. In addition, nitrogen dilution seems to be favorable factor also in improving cycle efficiency.

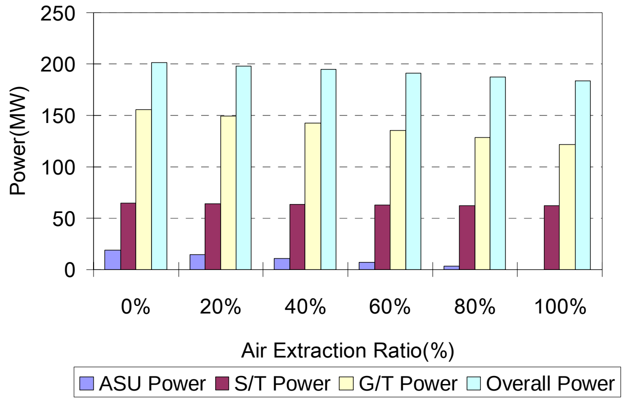

Fig. 10. Power of Coal IGCC without N_2 dilution.

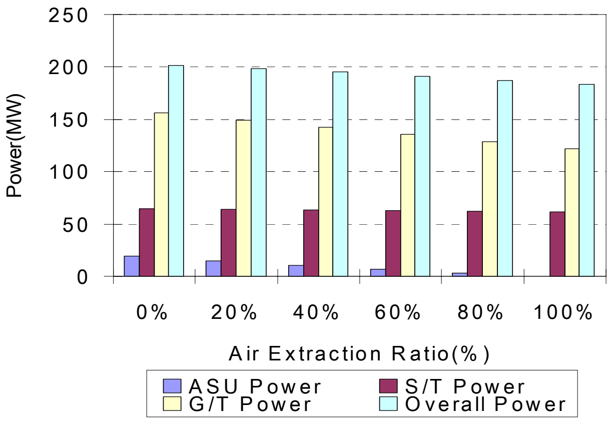

Fig. 11. Power of HRO IGCC without N_2 dilution.

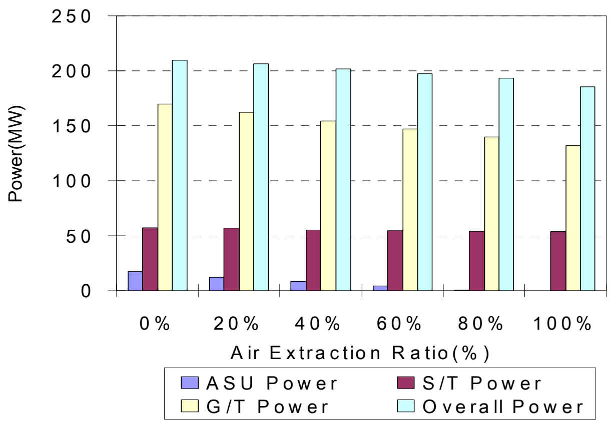

Fig. 12. Power of Coal IGCC with N_2 dilution.

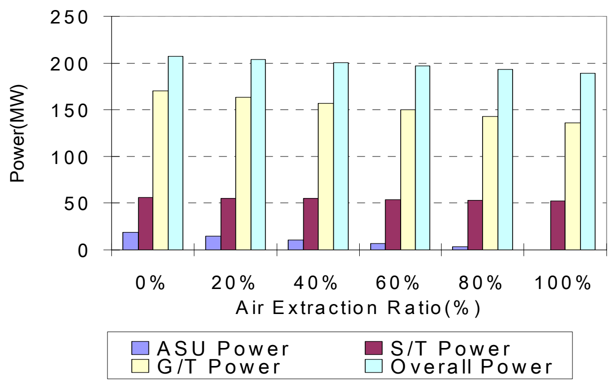

Fig. 13. Power of HRO IGCC with N_2 dilution.

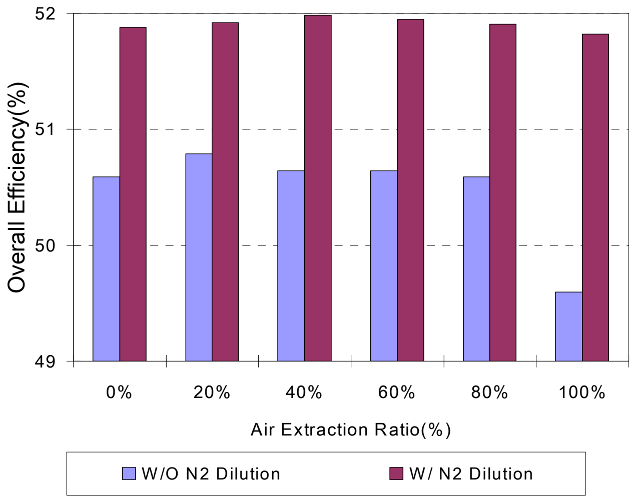

Fig. 14. Efficiency of Coal IGCC.

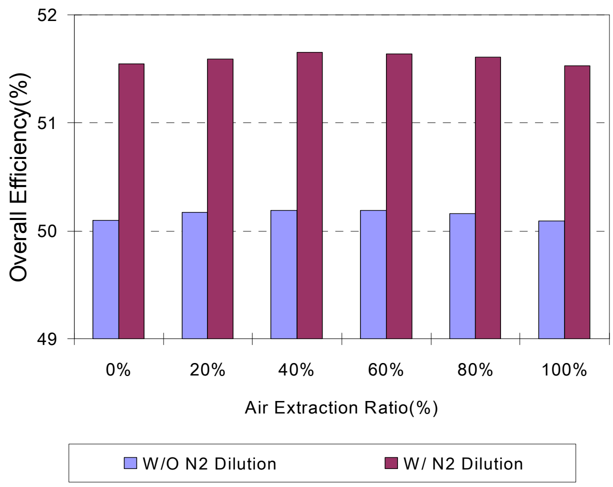

Fig. 15. Efficiency of HRO IGCC.

Figures 16 and 17 illustrate how the pressure ratio of gas turbine varies at different air extraction and nitrogen dilution conditions. As described before, the decrease of air extraction ratio causes the compressor air flow reduction accompanying with the rise-up of pressure ratio from the design-point(pressure ratio=15) along the compressor characteristic curve. If further deviation from the design point might be possible due to the ASU integration at low air extraction and with nitrogen dilution, it could cause gas turbine to operate at near surge condition (pressure ratio »17), the well-known instability phenomena of turbomachinery. From the previous results of Figs.10-15, low air extraction and nitrogen dilution seem favorable design criteria in improving net power output and efficiency, but they are negative to secure stable operation of IGCC. Therefore, at the actual IGCC design stage, some compromise between performance and stable operation of IGCC should be made for determining ASU integration design.

Figures 18 and 19 depict the NOx emission levels and how NOx can be reduced by ASU integration design. Heavy residue oil IGCC is environmentally superior to the coal IGCC because the operating combustor pressure of coal IGCC is somewhat higher than the HRO IGCC. In addition, nitrogen dilution is shown to be very strong parameter for

NOx reduction while air extraction ratio is minor one. Although the NOx emission of IGCC gas turbine can be reduced by nitrogen dilution, its level is relatively higher than the natural gas firing. This result implies that additional NOx control techniques such as nitrogen saturation and steam injection must be employed along with nitrogen dilution for achieving more NOx reduction.

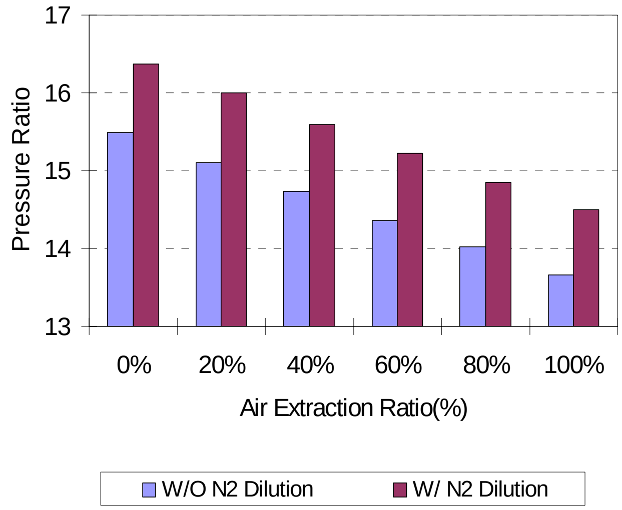

Fig. 16. Gas Turbine Pressure Ratio of Coal IGCC.

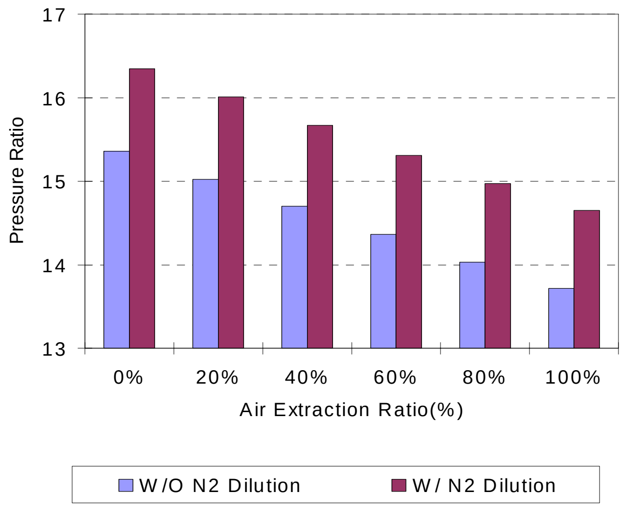

Fig. 17. Gas Turbine Pressure Ratio of HRO IGCC.

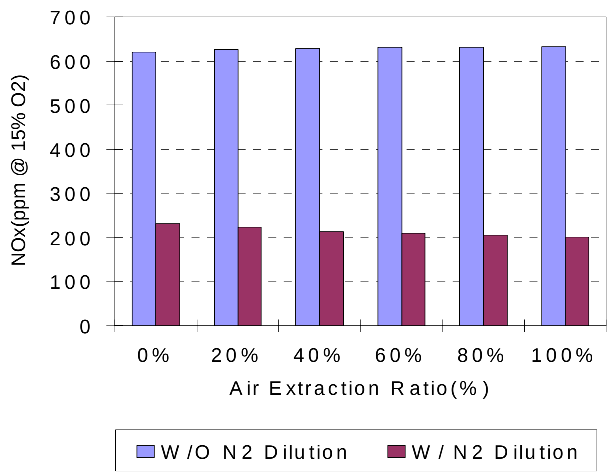

Fig. 18. NOx Emission of Coal IGCC.

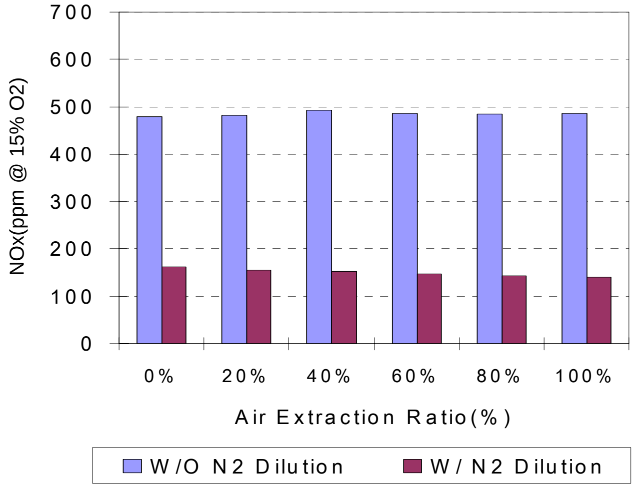

Fig. 19. NOx Emission of HRO IGCC.

4. CONCLUSIONS

A simulation method is developed for predicting the performance and the NOx emission of IGCC power plant integrated with ASU. The present prediction results show that the power of IGCC are significantly reduced with the increase of air extraction, and the highest IGCC efficiency can be achieved at optimal air extraction ratio range within 20-40%. The nitrogen dilution of combustor favorably affects performance improvement as well as NOx emission reduction of IGCC. But, with decreasing air extraction ratio and/or applying nitrogen dilution, the operation condition of gas turbine is shifted toward off-design point and further unstable operation point. Compared with heavy residue oil IGCC, the coal IGCC is superior in the aspects of power and efficiency while showing higher NOx emission level.

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