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Effect of air separation unit integration on integrated gasification combined cycle performance and NO_x emission characteristics

Chan Lee†, Seung Jong Lee* and Yongseung Yun*

Department of Mechanical Engineering, University of Suwon, Suwon 445-743, Korea
*Plant Engineering Center, Institute for Advanced Engineering, Suwon 442-749, Korea
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Abstract−Thermodynamic simulation method is developed and applied to analyze the performance and the NO_x 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 coal gasification and gas clean-up and the thermodynamic combined cycle model with NO_x prediction capability. With coal as feedstock of IGCC, the present study investigates and compares the power output, the overall efficiency and the NO_x 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.

Key words: Gasification, Gas Cleanup, ASU Integration, Air Extraction, Nitrogen Dilution, NO_x Emission

INTRODUCTION

IGCC is being considered as a next generation fossil power plant type because of its higher overall cycle efficiency and superior environmental performance compared with conventional coal-fired boiler power plants, so it is expected to be a very suitable power plant option for meeting worldwide climate change regulations and standards in the near future. However, because IGCC typically shows a very complicated process combination of gasification, gas clean-up, gas turbine, steam cycle and ASU systems with various energy and mass integration schemes affecting the overall performance and emission characteristics of IGCC [1,2], it is very difficult for the design engineers in the power industry to determine the optimum integration condition of the subsystems.

In general, the heating value of the syngas fuel is about 20-30% of the natural gas, so the IGCC gas turbine combustor requires 4-5 times fuel consumption of the syngas compared with a natural gas combustor at the same turbine inlet temperature (TIT) conditions. Another different feature of IGCC from conventional coal and natural gas power plants can be found in the ASU-gas turbine integration scheme. Air is extracted from gas turbine compressor and then is fed to the ASU, which separates air to oxygen for the oxidizer of coal gasification and nitrogen for the dilution agent of NO_x control in the gas turbine combustor. However, because most large industrial gas turbines for IGCC application are designed as natural gas firing units, so the low-Btu gas firing and the ASU integration of the gas turbine of IGCC make the operation condition of the gas turbine shift from the on-design point to the off-design point, which might cause unstable phenomena such as compressor surge and combustion instability [3,4]. For this reason, the design concept and the method of ASU-gas turbine integration must be very carefully selected with consideration of both the performance and the emission characteristics of IGCC power plants. However, previous IGCC simulation studies focused only on the on-design point performance evaluations by using thermo-chemical analyses [1,3,5,6], so they need to be revised to predict both the off-design effect of gas turbine and the NO_x 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 NO_x emission prediction capabilities. Furthermore, with the syngas fuel derived from coal, the present simulation method investigates the power output, the pressure ratio and the NO_x emissions of IGCC power plant by varying the ASU integration conditions.

IGCC SIMULATION METHODS

1. Gasification and Gas Cleanup Process Models

As shown in the process flow diagram of Fig. 1, the present study employs dry-feeding oxygen-blown coal gasification process and acid gas removal-Claus-SCOT process combination for the desulfurization of raw syngas.

In the present study, the coal 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

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

• Gas phase reactions

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

†To whom correspondence should be addressed.
E-mail: clee@suwon.ac.kr
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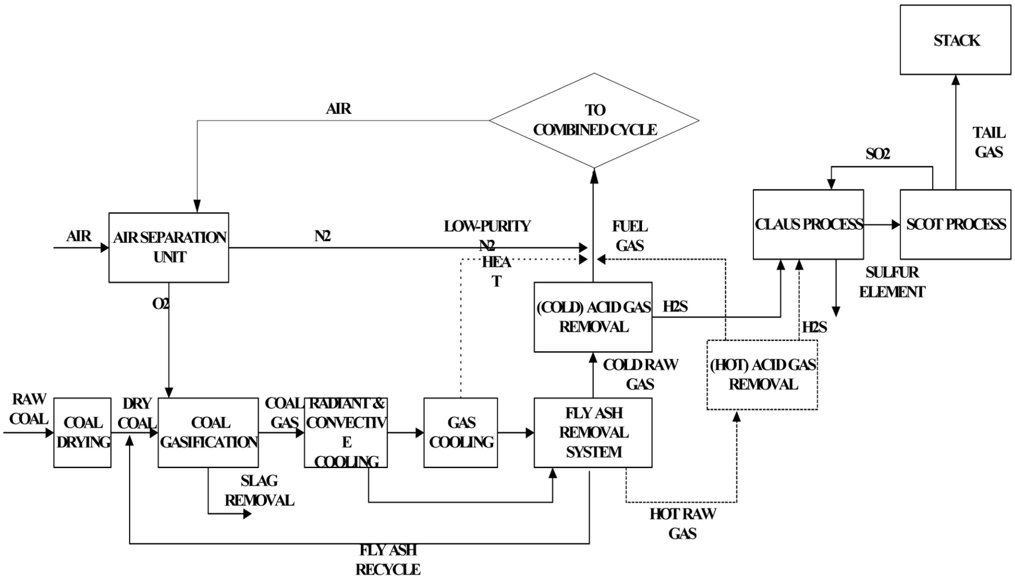

Fig. 1. Process flow diagram of IGCC power plant.

$$S+H_2 \leftrightarrow H_2S \tag{2}$$

In addition, the acid gas component in the raw syngas is removed by MDEA process and the desulfurization is conducted by a combination of Claus and SCOT processes. The present study uses the following reaction mechanisms for the MDEA, the Claus and the SCOT processes:

Gas-cleanup reaction model:

• MDEA process

$H_2S+CH_3(CH_2OHCH_2)_2N \leftrightarrow CH_3(CH_2OHCH_2)2NH^{+}+HS^{-}$

• Claus process

$H_2S+3\ O_2 \leftrightarrow SO_2+H_2O,$

$COS+3/2\ O_2 \leftrightarrow SO_2+CO_2,$

$$2\ H_2S+SO_2 \leftrightarrow 3\ S+2\ H_2O \tag{3}$$

• SCOT process

$COS+H_2O \leftrightarrow H_2S+CO_2,$

$SO_2+3\ H_2 \leftrightarrow H_2S+2\ H_2O,$

$$CO+H_2O \leftrightarrow CO_2+H_2 \tag{4}$$

Here, the details about modeling techniques and chemical kinetic data of the above chemical reactions are well described in the ASPEN Plus user manual and the MDEA's experimental observation [7,8].

Table 1. Syngas fuel conditions

Component	Composition (vol%)
H_2	29.33
CO	64.57
CO_2	0.71
H_2O	0.14
CH_4	0.04
N_2	4.49
Ar	0.72
LHV(kJ/kg)	12358.4

In the present study, Datong bituminous coal is used as the feedstock of IGCC, the 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 at the optimum point are summarized also in Table 1 and then they are used as the input data for the gas turbine combustor of combined cycle simulation.

2. ASU-Gas Turbine Integration

As mentioned before, in IGCC power plants, ASU and gas turbines are integrated through air and nitrogen streams. Fig. 2 shows a 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 NO_x 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) can be the main design pa-

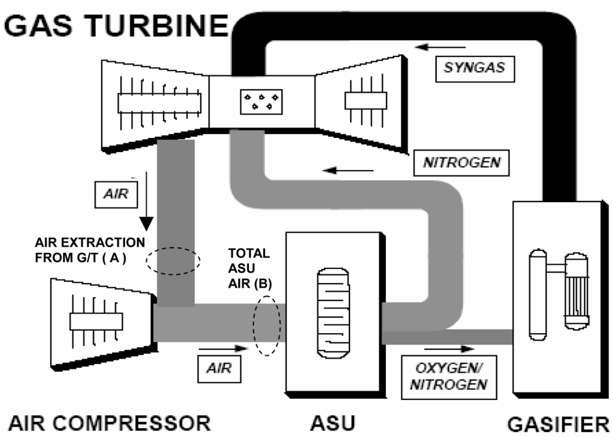

Fig. 2. Air/N_2 integration between gas turbine and ASU.

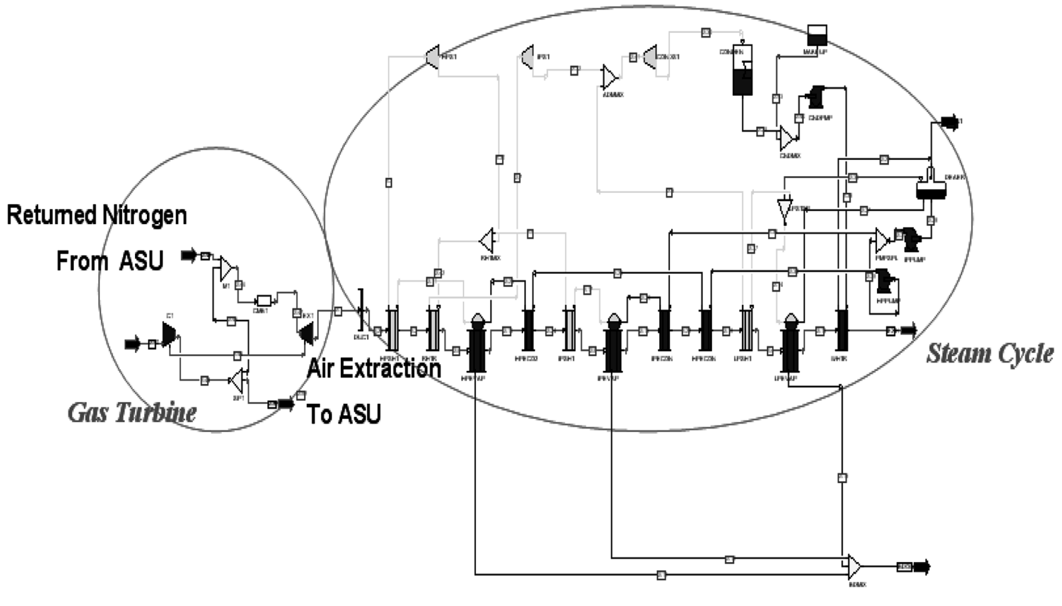

Fig. 3. Combined cycle simulation model.

rameter in the ASU-gas turbine integration design. In addition, nitrogen dilution also seriously affects the performance and the emission of IGCC power plants [3].

3. Combined Cycle Model

3-1. Topping Cycle

As shown in Fig. 3, 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 [9] with user-supplied model for NO_x emission prediction. The present study also assumes the ASU as double distillation column type.

For the analysis of the present study, GE's MS7001FA machine 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 and 1,288 ºC, respectively [10]. In gas turbine modeling, the 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. The combustor model calculates heat and mass balances for three incoming streams of the air from the compressor, the returned nitrogen from ASU and the clean syngas fuel through upstream chemical processes. In addition, the present combustor analysis method can predict the NO_x emission level by applying the semi-analytical model of Lefebvre [11] expressed as the following equation:

$$NO = \frac{\alpha P^{1.2}\exp(0.009T_{pz})}{m_{air,pz}T_{pz}(\Delta P/P)^{0.5}} \quad \text{[g/kg]} \tag{5}$$

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 the gas turbine-specific constant, so it is tuned by using the MS7001FA's actual test data for NO_x emission when burning natural gas [12].

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 [13] for both natural gas firing and IGCC cases as follows:

$$\frac{(m_{air}+m_{CG}+m_{N_2})\sqrt{TIT}}{PA_t} = \frac{(m_{air}+m_{NG})\sqrt{TIT}}{PA_t} = \text{const} \tag{6}$$

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 the gas turbine burns the syngas and integrates with ASU, the air flow condition of compressor is shifted to off-design point where the corresponding pressure ratio and efficiency are determined

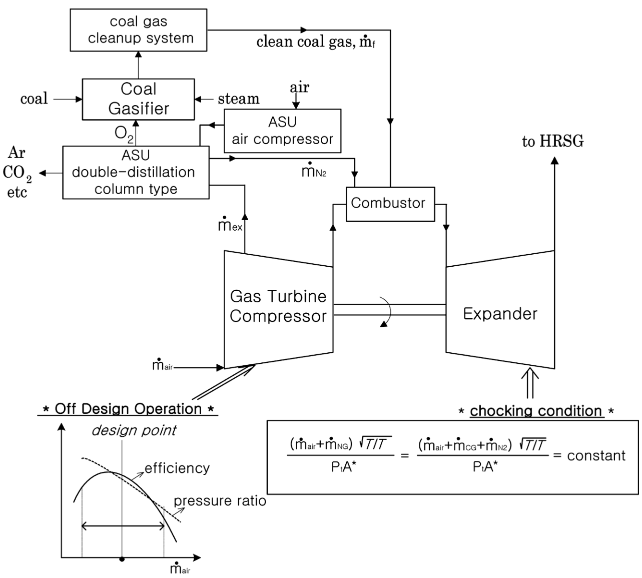

Fig. 4. Schematic diagram of the gas turbine integrated with ASU.

from the characteristic curve as shown in Fig. 4 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 Eq. (6) that the mass addition effect at expander inlet due to ASU integration causes changes in compressor air flow and pressure ratio along the performance curve depicted in Fig. 5. Here, the compressor performance curve used in this study is obtained from the generalized maps of the GateCycle library [9].

3-2. Bottoming Cycle

Bottoming cycle design has significant impacts on the overall combined cycle performance 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 [4]. Finally, the present steam cycle is designed at main steam conditions of 103 kg/cm^2 and 538 °C, a stack flue gas temperature above 100 °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.

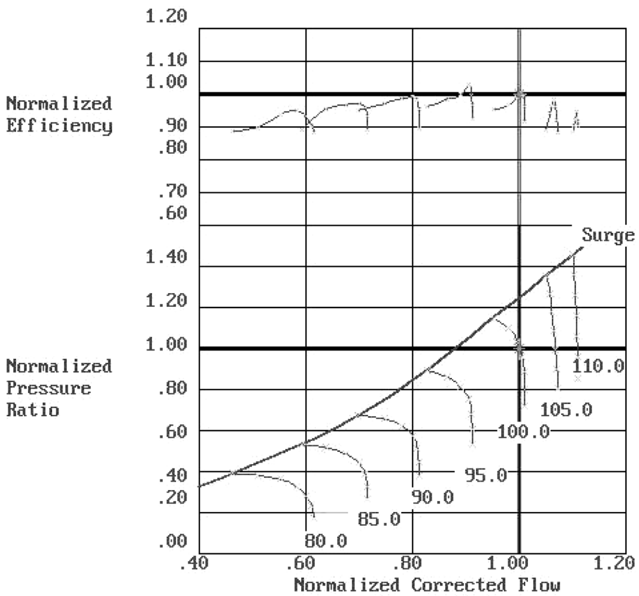

Fig. 5. Generalized performance map of compressor.

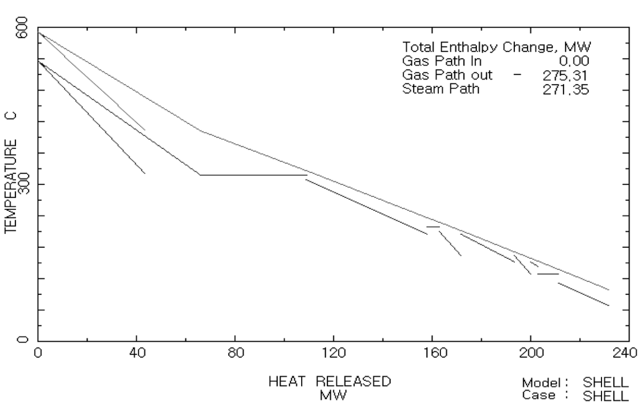

Fig. 6. Temperature profiles of flue gas and water/steam.

As shown in Fig. 3, 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

Fig. 6 also shows the temperature profiles of flue gas and water/steam along the above HRSG arrangement when the MS7001FA gas turbine is used as the topping cycle.

SIMULATION RESULTS AND DISCUSSIONS

The predicted performance results by the present method are favorably compared with the actual test results of the Seo-Inchon combined cycle power within a relative error of 5%, which shows the reliability of the present method in the use of IGCC simulation. For the verification of the NO_x prediction method, the present NO_x model is applied to the natural gas firing combustor of a General Electric gas turbine system because of the lack of the NO_x emission test results of the IGCC power plant. The NO_x emission prediction results well agree with the combustor test results of the General Electric [12] at various steam injection conditions within a relative error of 10% as shown in Fig. 7.

Figs. 8 and 9 show the net power outputs of IGCC power plants without or with nitrogen dilution for the gas turbine combustor. Please note that ASU power contains the power consumption of the supplementary air compressor and distillation column process. With

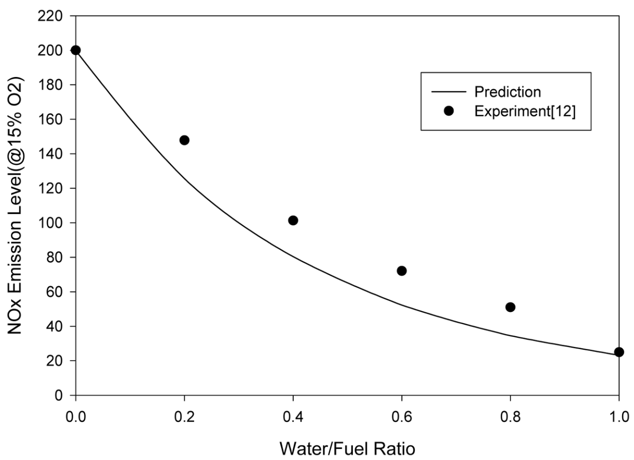

Fig. 7. NO_x emission of natural gas firing MS7001FA gas turbine.

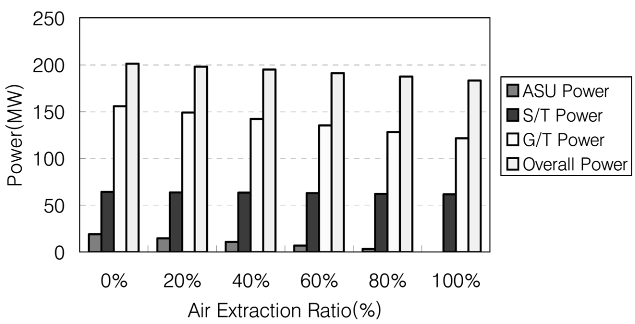

Fig. 8. Power of coal IGCC without N_2 dilution.

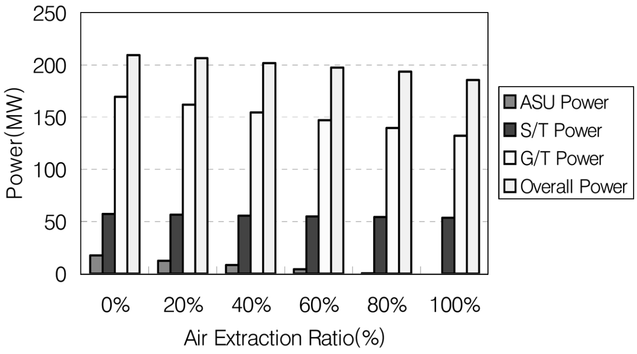

Fig. 9. Power of coal IGCC with N_2 dilution.

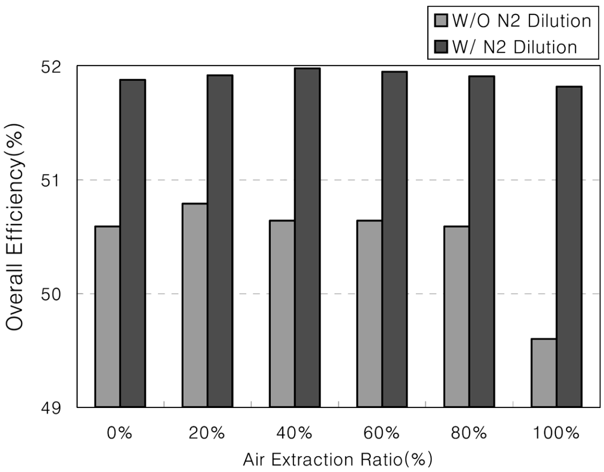

Fig. 10. Combined cycle efficiency of coal IGCC power plant.

the decrease of air extraction ratio, the gas turbine power, the steam turbine power and the ASU are increased in a similar manner. These tendencies are explained from the fact that a lesser 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. As also shown in Figs. 8 and 9, nitrogen dilution shows a remarkable effect on power enhancement because of the large nitrogen mass addition into the turbine expander.

Fig. 10 shows the overall combined cycle efficiencies ranging within 49-52% based on LHV. The best combined cycle 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 a favorable factor also in improving cycle efficiency. Please note that, in the present study, the combined cycle efficiency is defined by using the net power output of the power block of the IGCC power plant and the power consumption of ASU. So, if the auxiliary power consumptions required in coal mills and other pre-treatment equipment are considered, the actual overall IGCC power plant efficiency may be somewhat reduced from the predicted combined cycle efficiency.

Fig. 11 illustrates 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 a compressor air flow reduction accompanied with the rise-up of pressure ratio from the design-point (pressure ratio=15) along the compressor charac-

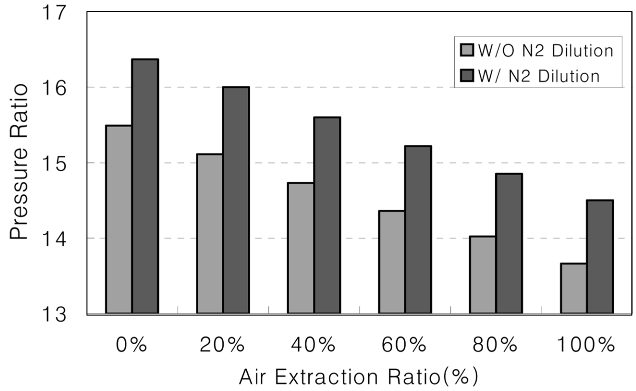

Fig. 11. Gas turbine pressure ratio of coal IGCC power plant.

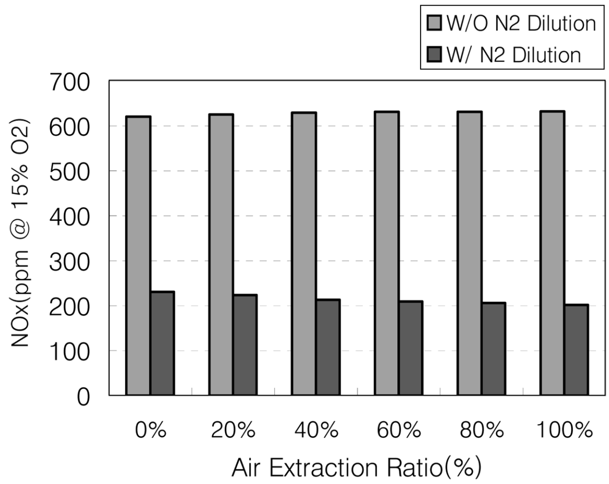

Fig. 12. NO_x emission of coal IGCC power plant.

Table 2. Comparison between simulation and test results

Parameter	Simulation result	Test result
GT power (MW)	152.88	152.73
ST power (MW)	78.96	78.97
Cycle efficiency (%)	53.88	54.02
GT exhaust temp. (°C)	587.40	587.17
Fuel consumption (kg/s)	8.72	8.61

teristic curve. If further deviation from the design point might be possible due to the ASU integration at lower air extraction and with nitrogen dilution, it could cause the gas turbine to operate at near surge condition (pressure ratio≈17), the well-known instability phenomena of turbomachinery. From the previous results of Figs. 8-11, low air extraction and nitrogen dilution seem favorable design criteria in improving net power output and efficiency, but they are acting negatively 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.

Fig. 12 depicts the NOx emission from the IGCC power plant and how NO_x emission level can be reduced by ASU integration design. Nitrogen dilution is shown to be a very strong parameter for NO_x reduction, while air extraction ratio is a minor one. Although the NO_x emission of IGCC gas turbine can be reduced by nitrogen dilution, its level is still relatively higher than the natural gas firing case. This result implies that additional NO_x control techniques such as nitrogen saturation and steam injection must be employed along with nitrogen dilution for achieving more NO_x reduction.

CONCLUSIONS

A simulation method is developed for predicting the performance and the NO_x emission of an IGCC power plant integrated with ASU. The present prediction results show that the power of the IGCC is 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 the combustor favorably affects performance improvement as well as NO_x emission reduction of IGCC. But, with decreasing air extraction ratio and/or applying nitrogen dilution, the operation condition of the gas turbine may be shifted toward off-design point and further unstable operation point.

ACKNOWLEDGMENT

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NOMENCLATURE

A_t : turbine throat area [m^2]
m : mass flow rate [kg/s]
T : temperature [K]
TIT : turbine inlet temperature [K]
P : pressure [Pa]
ΔP : pressure drop [Pa]

Greek Letters
α : gas turbine specific constant

Subscripts
air : air
CG : coal gas
N_2 : nitrogen
NG : natural gas
pz : primary zone

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