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Analysis of the impact of gas turbine modifications in integrated gasification combined cycle power plants

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ABSTRACT

In an IGCC (integrated gasification combined cycle) plant, the operating environment of the gas turbine (GT) deviates from the design conditions due to its integration with both the gasifier and the air separation unit (ASU). In particular, a trial to design the entire system with low GT–ASU integration would cause a decrease in the compressor surge margin and the turbine blade overheating. In this study, modification of the turbine and compressor to avoid a decrease in the surge margin and overheating was simulated, and the result was compared with the case without modification. The entire IGCC plant was modeled and the full off-design operation of the gas turbine was simulated. Under-firing and a decrease in dilution nitrogen can mitigate the two problems without component modification but inevitably cause a considerable performance penalty in the low integration degree regime. Both turbine modification (annulus area increase) and compressor modification (increase in the surge pressure ratio) enabled a continuous increase in power and efficiency with decreasing integration degree. In the very low integration degree regime, the power benefits of the two modifications were similar and considerable. A sensible power boost can be achieved if the turbine coolant modulation can be adopted instead of under-firing in modification strategies.

1. Introduction

Worldwide efforts are being devoted to the research and development of electric power production from coal in both an efficient and environmentally friendly manner. Among these studies, the integrated gasification combined cycle (IGCC) is considered the most environmentally friendly method of using coal. Several plants are in commercial operation and the number of installed IGCC plants is increasing steadily [1]. Along with the commercialization efforts, a range of fundamental studies on the performance and operability have been reported. These include performance analysis and a comparison of existing plants [2], evaluation of the cost and performance baselines [3], and the effect of the design options such as GT–ASU integration and nitrogen dilution on IGCC system performance [4,5]. Recent works have dealt with part load performance [6] and dynamic operations [7] of IGCC plants. Efforts to enhance the IGCC system efficiency by improving the gasification process have also been made [8]. The high potential of incorporating relatively economical and efficient CO_2 capture is another reason to choose IGCC. Various studies have been carried out including the dependence of IGCC performance on the operating parameters of the pre-combustion capture technology [9] and comparisons between the absorption based capture (the most frequently considered) and the other emerging technologies such as membrane separation [10], chemical looping [11] and oxy-fuel combustion technologies [12]. Recent studies also include an analysis of the influence of GT–ASU integration on the performance of IGCC plants with carbon capture [13] and an integrated performance and economic analysis [14].

An IGCC plant is composed of two major parts: the power block and gasifier block. Although the power block of an IGCC plant looks the same as those in conventional combined cycle plants, there are several key differences because it is integrated with the gasifier block, and the operating environment is different from the original condition. The heating value of syngas, which consists mainly of carbon monoxide and hydrogen, is much lower than that of natural gas, which gas turbines are normally designed for. Therefore, much more fuel is supplied to the gas turbine than with natural gas operation. The most effective strategy to design an IGCC plant is to use an existing gas turbine. Of course, combustor modification is inevitable. The remaining issue is whether modifications in the turbomachinery parts (compressor and turbine) are necessary.

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Nomenclature

A	area (m^2)
ASU	air separation unit
C	cooling constant
c_p	specific heat (kJ/kg K)
GT	gas turbine
HHV	higher heating value (kJ/kg)
HP	high pressure
ID	integration degree
IGCC	integrated gasification combined cycle
IP	intermediate pressure
LP	low pressure
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
PR	pressure ratio
R	gas constant (kJ/kg K)
S1, S2, S3, S4	design strategies
SM	compressor surge margin
ST	steam turbine
T	temperature (K)
TRIT	turbine rotor inlet (firing) temperature (K)
$\dot{W}$	power (MW)
ϕ	cooling effectiveness
γ	specific heat ratio
η	efficiency
κ	constant

Subscripts

Aux	auxiliary
b	blade metal
c	coolant
d	design point
g	gas
in	inlet
p	polytropic

The gas turbine is integrated with the air separation unit, which produces an oxidant for the gasification process. The air to the ASU can be fed either by an independent air compressor or by the compressor of the gas turbine (or a combination of both). A wide range of integration methods are available in commercial plants [2,15]. Integration is the primary design factor of the IGCC plant, which affects the plant performance considerably [5]. The operating conditions of the gas turbine in IGCC plants deviate from the original design condition if its turbomachinery parts are not modified. The reduction of the compressor surge margin [4,5] and the increase in turbine blade temperature [16,17] can be critical issues depending on the GT–ASU integration. The type of syngas also affects the operability and performance of the gas turbine [18]. The main reason for these problems is that the turbine inlet gas flow increases considerably due to the much lower heating value of the syngas than natural gas, and additional air is supplied by the auxiliary compressor in designs with a degree of integration less than 100% [16]. As the integration degree (ID) decreases (air supply from the auxiliary compressor to the ASU increases), the power and efficiency of the IGCC can increase but the surge margin reduction and turbine blade overheating become more severe [16]. These two problems can be alleviated by modulating the gas turbine parameters, such as the firing temperature and diluting nitrogen flow, but such a solution is accompanied by a deterioration of plant performance [16].

A more active solution to avoid the surge margin reduction is to modify the engine components. The first option is to increase the swallowing capacity of the turbine by widening the turbine annulus area, i.e. flow path. The need to increase the turbine annulus area for IGCC applications has been acknowledged by gas turbine manufacturers, and such a modification has been adopted in some commercial IGCC plants [3,19,20]. A brief discussion on the usefulness of the turbine modification was presented in a cycle simulation [5]. An increase in the turbine annulus area is also useful in gas turbine based plants using low calorific gases [21] because an increase in turbine flow is a common phenomenon in those plants. A recent study [22] suggested gas turbine modifications, especially turbine annulus re-design, to use various low calorific syngas fuels, but did not consider the syngas production process and the influence of GT–ASU integration on the entire system performance. Another re-design option is to add a couple of compressor stages to increase the maximum (surge) pressure ratio, thereby increasing the surge margin. This concept was mentioned in a manufacturer's report [23] and a sample calculation was presented in a cycle simulation to illustrate its effect [5]. On the other hand, although such modifications alleviate the problem of compressor operation, they can aggravate the problem of the overheating of hot sections. The simplest solution is to reduce the firing temperature [3] but this penalizes the system performance considerably.

Therefore, the issue of gas turbine modification for use in IGCC plants is an important fundamental design factor that needs to be investigated thoroughly. Although several pieces of information on the purpose and effect of the compressor and turbine modifications are available, as illustrated above, they provide only fragmentary knowledge. In this regard, a systematic overview of the effect of the modifications, particularly a comparison of different modification strategies, is needed. This study examined the effects of turbine and compressor modifications on the IGCC performance, considering the limitations on both the compressor surge margin and turbine blade temperature. An entire IGCC plant including a gasifier block, gas turbine and bottoming steam cycle was modeled. A full off-design analysis of the gas turbine was used to account for the change in operating conditions. First, the dependence of the plant performance on the degree of integration subject to the limitations of a compressor surge and turbine blade temperature is shown. The performance of the IGCC plant designed with a modified gas turbine was then analyzed and compared with the case using an unmodified gas turbine.

2. System modeling

An entire IGCC plant was modeled, as shown in Fig. 1. The system included the power block that consists of a gas turbine and a bottoming steam turbine cycle. Also included in the analysis are the gasification block and ASU, which interact with the gas turbine. The Shell gasification process was simulated using HYSYS [24] based on the process layout and data reported in literature [25]. A sophisticated model was made to include all the components in the reference. Because this paper focuses on the performance of the power block, detailed descriptions of the gasifier block modeling will not be given here. Readers can refer to Ref. [26], which reports the results of a simulation of the same process. Tables 1 and 2 show the properties of coal and the major parameters of the ASU and the gasifier, Table 3 shows the syngas properties. The very close agreement between the simulation and reference [25] in the compositions and heating value of the syngas produced shows the