

Analysis and optimization of a solid oxide fuel cell and intercooled gas turbine (SOFC–ICGT) hybrid cycle

Yaofan Yi, Ashok D. Rao, Jacob Brouwer, G. Scott Samuelsen*

Advanced Power and Energy Program/National Fuel Cell Research Center, University of California, Irvine, CA 92697-3550, USA

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Abstract

The power generation community faces a major challenge: to protect the environment while producing a plentiful supply of clean low-cost energy. “21st Century Energy Plants” (Vision 21 Plants) have been proposed and conceptualized to meet the energy and environmental challenges. The solid oxide fuel cell and intercooled gas turbine (SOFC–ICGT) hybrid cycle introduced in this work is one example of a Vision 21 Plant. The system includes an internal-reforming tubular-SOFC, an intercooled gas turbine, a humidifier, and other auxiliary components. A recently developed thermodynamic analysis computer code entitled advanced power systems analyses tools (APSAT) was applied to analyze the system performance of the SOFC–ICGT cycle. Sensitivity analyses of several major system parameters were studied to identify the key development needs and design and operating improvements for this hybrid cycle. A novel optimization strategy including a design of experiments (DOEx) approach is proposed and applied to the hybrid system. Using this optimization strategy, a system electrical efficiency higher than 75% (net ac/lower heating value (LHV)) could be achieved when the system was designed to operate under a high operating pressure (50 bara) and with a low percent excess air (EA) (55%) in the SOFC.

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1. Introduction

The Vision 21 program of the US Department of Energy proposes a new approach to produce energy that addresses pollution control as an integral part of high-efficiency energy production in a “Vision 21 Energy Plant”. Integral pollution control, ultra-high efficiency, and potential for carbon dioxide capture and sequestration are the salient features of a Vision 21 energy plant concept. Vision 21 energy plants are also expected to produce value added products other than electricity such as hydrogen or liquid transportation fuels. The fuel-to-electricity conversion efficiency goal of a Vision 21 energy plant is greater than 60% (higher heating value (HHV) basis) using coal as fuel source and greater than 75% (lower heating value (LHV) basis) using natural gas. Currently, the corresponding efficiencies for most operating coal-fueled power plants are between 33 and 35%, and for operating natural gas-fueled plants typical efficiencies range from 45 to 55%. A Vision 21 plant is also required to have near zero emissions of criteria pollutants, including smog-

and acid rain-forming pollutants, and reduce greenhouse gas emissions (CO₂) by 40–50% by efficiency improvements (with further reductions in greenhouse gas emissions if coupled with carbon sequestration) [4].

Previous work by Rao and Samuelsen [10] investigated various advanced cycles including gas turbine combined cycles, humidified air turbine cycles, oxygen–hydrogen-fired direct Rankine cycles, and hybrid fuel cell gas turbine cycles. These analyses determined that fuel cell gas turbine hybrid cycle technology is key to reaching the Vision 21 efficiency and emissions goals.

Recently, several fuel cell gas turbine hybrid system configurations have been suggested by various research groups around the world.

The Department of Heat and Power Engineering at Lund University in Sweden has conducted theoretical studies of hybrid SOFC/GT systems. Five parameters were studied in a reference system, including turbine inlet temperature (TIT), cell voltage, compressor pressure ratio, air flow rate, and air inlet temperature. A maximum electrical efficiency of 65% (LHV) was found at a pressure ratio of two [8].

Chan et al. [2] of the Nanyang Technological University, Singapore conducted two case studies on the SOFC/GT hybrid system with particular attention to the effects of op-

* Corresponding author. Tel.: +1-949-824-5468; fax: +1-949-824-7423.
E-mail address: gss@nfcrc.uci.edu (G.S. Samuelsen).

erating pressure and fuel flow-rate on the performance of the components and overall system. Results showed that an internal-reforming hybrid SOFC/GT system could achieve an electrical efficiency of more than 60% (LHV).

A fossil fuel based hybrid SOFC/GT system with liquefaction recovery of carbon dioxide was proposed by Inui et al. [5]. Results showed that the total thermal efficiency of the system using natural gas as the fuel reached 70.64% (LHV).

Some research groups have investigated and presented the part-load performance of hybrid SOFC/GT systems in addition to design point performance. These research groups have produced analyses such as those presented by Campanari [1], Costamagna et al. [3], and Kimijima and Kasagi [6]. These studies suggest that expected electrical efficiencies of hybrid systems are limited to 65% at design-point or part-load operation.

Previous research work conducted at the National Fuel Cell Research Center of the University of California, Irvine (NFCRC/UCI), which was limited to hybrid systems of less than 20 MW output, showed that the efficiency goal of the Vision 21 program was achievable with small hybrids. This was found to be the case despite having turbomachinery components with limited efficiencies (due to the smaller size). However, achieving an efficiency of 75% at this scale required a complex cycle including a reheat gas turbine with two SOFCs, one upstream of the high pressure expander and one upstream of the low pressure expander when limiting the operating pressure of the SOFC to 15 bara [9].

Although many researchers have analyzed hybrid fuel cell gas turbine systems as noted above, no optimization strategy has been proposed, which may be a reason for predicted limitations in the achievable system efficiency.

A multi-disciplinary team led by the NFCRC/UCI proposes herein to define the system engineering issues associated with the integration of key components and subsystems into large size (300 MW central station) power plant systems that meet the performance and emission goals of Vision 21.

The NFCRC team is conducting a detailed study of Vision 21 Energy Plants that includes: (1) developing a consistent analysis strategy to identify those combinations of fuels and fuel handling/processing systems, power generation components, and emission control systems that meet Vision 21 goals; (2) conceptualization of cycle configurations that have the potential to meet Vision 21 goals; (3) accomplishing detailed analyses of the resulting energy plants identifying key technical, operability, and economic factors that would affect the integration of the components and subsystems into a viable Vision 21 energy plant; and (4) making recommendations for R&D that address the issues that need to be resolved to assure successful system integration into a viable Vision 21 power plant [7]. As a milestone in the third step, the current SOFC–ICGT hybrid cycle is presented and optimized as the first Vision 21 power plant capable of meeting Vision 21 goals.

2. SOFC–ICGT system description

The Vision 21 hybrid cycle studied in this work is a solid oxide fuel cell integrated with an intercooled gas turbine system (SOFC–ICGT) as shown in Fig. 1. The system operating pressure can be designed as high as 50 bara. In the SOFC–ICGT cycle, two compressors (a low pressure and a high pressure compressor (HPC)) combined with an intercooler are utilized, to limit the operating temperature in the high-pressure stages of the compressor as well as reduce the compression power required. The compressed air provides the oxygen required by the SOFC stacks. Natural gas fuel is supplied at a pressure of 20.7 bara, is desulfurized and then humidified and preheated in a counter-current humidifier. The fuel gas leaving the humidifier at its dew point is then superheated by the turbine exhaust in the recuperator before entering the internal-reforming tubular-SOFC. The high temperature and pressure effluent from the SOFC is expanded through turbines to drive the compressors and an ac generator. Turbine exhaust, after superheating the fuel in the recuperator, provides heat to the humidifier circulating water in an economizer before leaving the system.

A humidifier is applied in the current cycle to improve the performance of the system, facilitate steam reformation of the natural gas, and prevent cooking in downstream elements. The humidifier also allows the recovery of low temperature heat from the turbine exhaust, preheats the fuel, and increases the power output from the turbine. The water exiting from the bottom of the humidifier, together with the make-up water, is circulated to recover heat from the turbine exhaust. The make-up water accounts for the water evaporated within the humidifier into the fuel stream while the blow-down from the humidifier limits the build up of solids within the humidifier.

Note that the solution strategy used in the internal reforming tubular SOFC includes the recycle of a portion of the anode exhaust gas (~60%), which is combined with the superheated fuel gas entering the SOFC. The internal reformers are interspersed between tubular SOFC cell bundles with the anode exhaust gas recycle providing enough water vapor and heat to facilitate partial steam reformation in the internal reformer, avoid carbon deposition in the reforming catalyst, and effectively remove heat from the SOFC stack. This strategy is typical of the design of Siemens Westinghouse Power Corporation.

3. Modeling

A special steady-state simulation tool—advanced power system analysis tool (APSAT), developed at the National Fuel Cell Research Center, was applied to simulate the SOFC–ICGT cycle. The detailed description of this simulation tool can be found in [9,10]. Fundamental thermodynamics, heat transfer, and equations of state appropriate for solving the complex and coupled chemical, electrochemi-

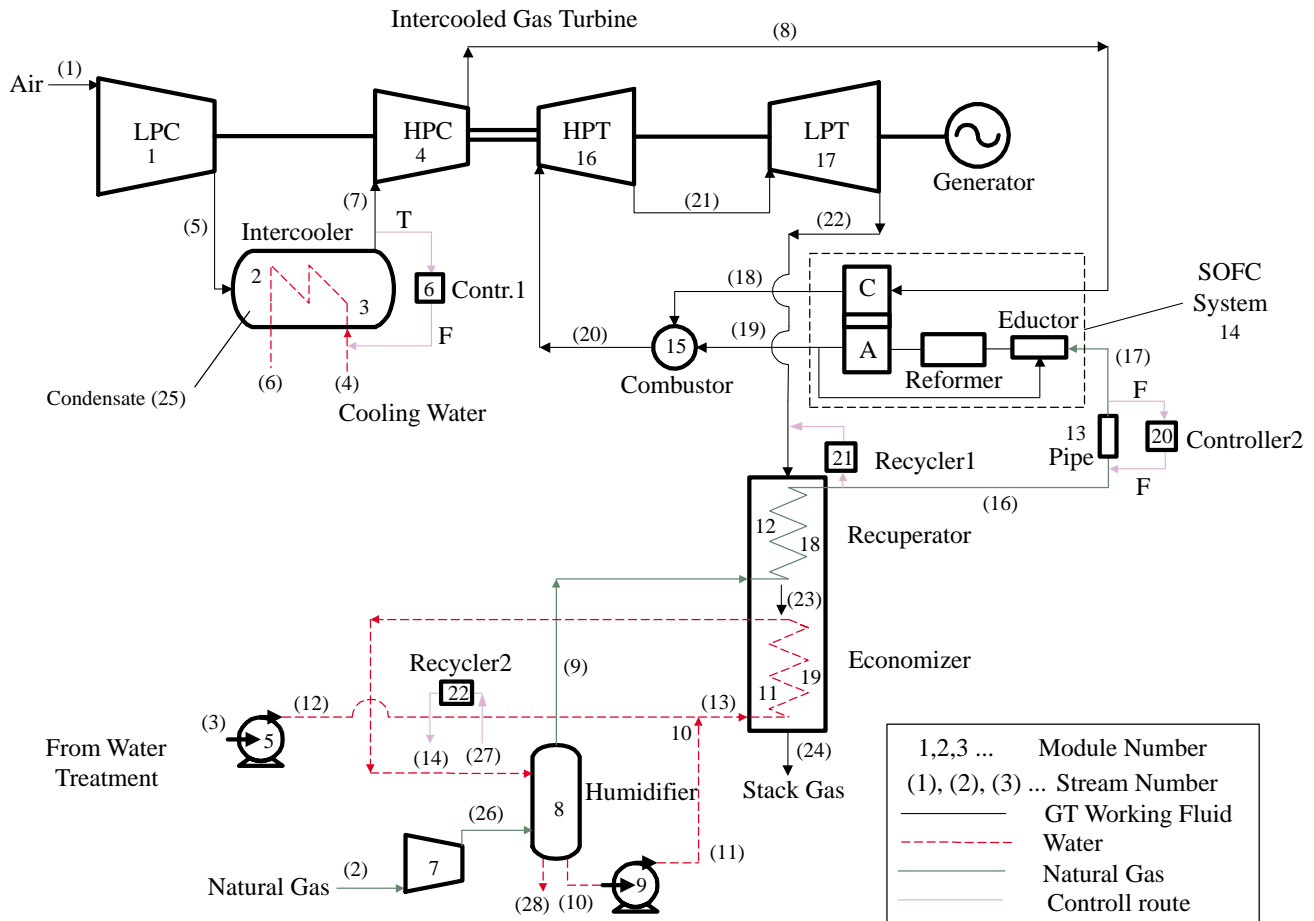


Fig. 1. SOFC-ICGT hybrid cycle: system configuration with identified modules and streams.

cal, heat, and mass transfer processes extant in high temperature fuel cell systems are included in APSAT. APSAT was verified to be a capable and accurate simulation tool in previous simulation work and comparisons to the Siemens Westinghouse 220 kW hybrid SOFC/GT system [12,13].

3.1. Basic parameter settings

In this study, it is assumed that all system components are working at their respective design conditions under steady-state operation. A set of operating parameters and the assumed efficiencies/effectiveness of these system components are given in Table 1. Note that the efficiencies and materials specifications presented in Table 1 require state-of-the-art components, but do not depend on advances beyond those possible today.

3.2. Simulation building

The SOFC-ICGT system with identified modules and streams is shown in Fig. 1. In this system, two controllers and two recyclers are applied to facilitate iterative solution of the complete system to satisfy all mass, momentum and energy balances within the design constraints. Controller

Table 1
Setting values of various parameters

Parameter	Setting value
Gas turbine (GT)	
Compressor isentropic efficiency (LPC) (%)	90
Compressor isentropic efficiency (HPC) (%)	88
Recuperator effectiveness (%)	90
Recuperator pressure drop (%)	2
Turbine isentropic efficiency (LPT) (%)	94
Turbine isentropic efficiency (HPT) (%)	92
GT firing temperature (°C)	<1700
Generator efficiency (%)	98.5
Solid oxide fuel cell (SOFC)	
Cell length (cm)	150
Cell outside diameter (cm)	2.2
Cell voltage (V)	0.7
Cell operating temperature (°C)	1000
Fuel utilization (%)	85
Stack heat loss (%)	2
Stack pressure loss (%)	2
dc-ac Converter efficiency (%)	95
Limiting current density (mA/cm ²)	350
Others	
Fuel inlet pressure (bara)	20.7 (300 psia)
Fuel compressor isentropic efficiency (%)	82
Motor efficiency (for pumps) (%)	92

1 is used to control the inlet temperature of high-pressure compressor by adjusting the mass flow rate of cooling water into the intercooler. Controller 2 can adjust the fuel flow from the source to meet the SOFC fuel requirement. Recycler 1 is used to maintain the effectiveness of recuperator at the specified value. Recycler 2 iteratively determines the required water flow to the humidifier.

4. Parametric analysis

Four basic parameters are studied in these analyses: (1) moisture content (MC) of the gas out of the humidifier (changed by controlling the water temperature out of the economizer); (2) excess air (EA) level in the SOFC (changed by varying the air flow rate when fuel flow rate is fixed); (3) overall compressor pressure ratio (π_{Overall}); and (4) intercooler location or pressure ratio of lower pressure compressor (π_{LPC}). The only response presented in this paper is the overall fuel-to-ac-electricity efficiency. The sensitivity of the efficiency to each of these parameters was studied. The definitions of the system efficiency and the net system power output in this study are given as follows:

System efficiency or overall fuel-to-ac-electricity efficiency

$$\eta_{\text{system}} = \frac{\text{net system power output}}{\text{lower heating value of fuel}} \quad (1)$$

Net system power output is equal to SOFC ac power after accounting for the inverter loss (but without transformer/busbar losses) plus gas turbine power at the generator terminals (but without transformer/busbar losses) minus all auxiliary power (for pumps, fuel compressor, etc.).

4.1. Moisture content of the gas out of humidifier

The effect of moisture content on the system efficiency was studied while setting the other three parameters as follows: LPC pressure ratio, 4; overall pressure ratio, 15.2; and excess air, 80%. The results presented in Fig. 2 show that increasing the content of moisture introduced in the fuel increases efficiency and net output initially. When the content of moisture is further increased, however, the efficiency and net output decrease. This behavior is caused by increasing moisture content that leads to both increased mass flow of the working fluid in the expanders and concurrent reductions in expander inlet temperatures for a given amount of excess oxygen in the SOFC. Initially the effect of increasing flow rate of the working fluid dominates and a net increase in the efficiency and net output is realized. When the moisture content of the fuel gas is further increased, the effect of lowering the inlet temperature to the expanders begins to dominate decreasing the efficiency and net output of the system.

A concern with increasing moisture content is the system cost. Notice that the moisture content is changed via

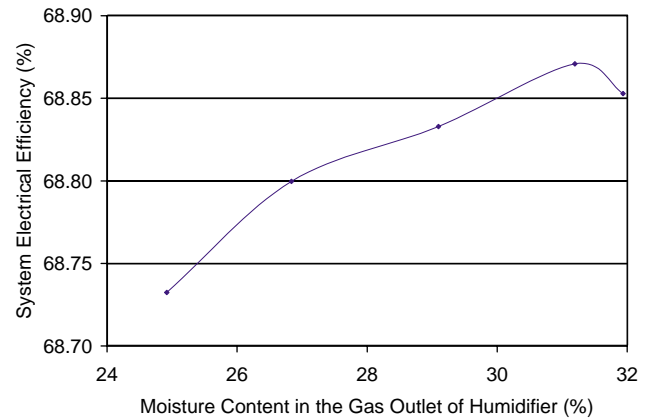


Fig. 2. Sensitivity of moisture content to the system efficiency, $\pi_{\text{LPC}} = 4$, $\pi_{\text{overall}} = 15.2$, EA = 80%.

varying the temperature of the water into the humidifier (or out of the economizer). When the water temperature out of the economizer is required to be higher, so as to achieve a higher moisture content in the gas exiting the humidifier, the required effectiveness of the economizer must be increased, leading to a higher economizer cost in practice. This economic tradeoff must be considered in practical design of such systems.

4.2. Excess air

The amount of excess air in this work is defined as the percentage of the excess air supplied that is greater than the stoichiometric amount divided by the stoichiometric amount. The effects of excess air were studied while maintaining LPC pressure ratio at 4, overall pressure ratio at 15.2, and moisture content of the gas out of the humidifier at 31%. Fig. 3 shows that with a decrease in excess air, the efficiency increases for a given fuel utilization within the SOFC. This is because the temperature of the working fluid entering the expander of the GT increases as the excess air decreases (note that no additional fuel is fired between the SOFC and the GT expander and only the unutilized fuel is combusted). Thus, for the same fuel utilization and electrochemical production, the requirement to heat less air results in higher turbine inlet temperature and higher overall system efficiency.

4.3. Overall compression ratio

The effects of overall compression ratio on system efficiency are presented in Fig. 4. The system efficiency increases monotonically with the overall compression ratio in the range of compression ratios studied. In this case, LPC pressure ratio was set to 4; excess air was kept at 80%, and moisture content was set to 29%. Higher efficiencies are realized at higher pressure ratios due to increased enthalpy in the expander inlet streams allowing more power production

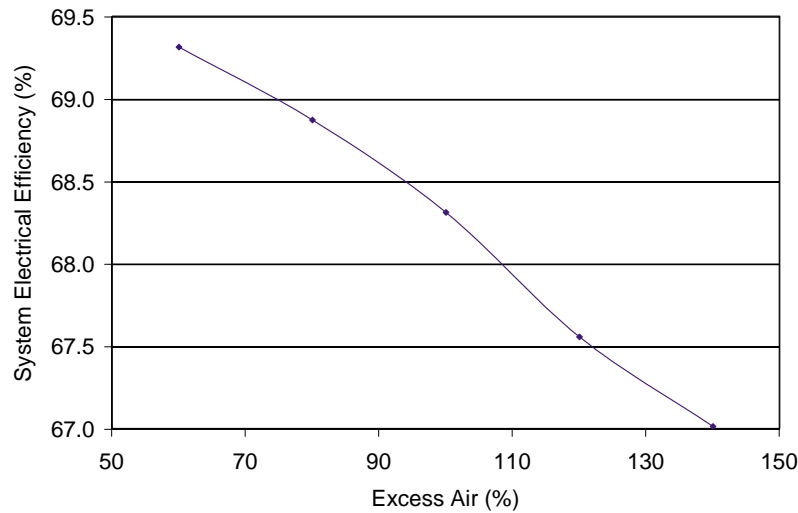


Fig. 3. Sensitivity of system efficiency to excess air, $\pi_{LPC} = 4$, $\pi_{overall} = 15.2$, MC = 31%.

in the gas turbine portion of the cycle. In the typical gas turbine cycle, this is usually balanced by increased compressor power demands. However, when the current hybrid system compression ratio increases, the fuel cell portion of the cycle increases in both output and efficiency, due to enhanced electrochemical kinetics. Therefore, although the compressors consume more power when the pressure ratio increases, the increase of the power produced in the expanders and the fuel cell is more than the increased compressor power demand within the range of pressures ratios investigated. Note that the current monotonic dependence and magnitude of increased performance with increasing pressure ratio depends not only on the overall system design, but particularly on the use of an intercooled compressor design as specified in Table 1.

4.4. Intercooler location

The results presented in Fig. 5 show that increasing LPC pressure ratio beyond three decreases efficiency when the

overall compression ratio is held constant (35 in this case). The reasons for this behavior are:

- With a higher LPC pressure ratio, the temperature of LPC outlet increases, and thus the temperature of air inlet to the intercooler increases. In this case, the temperature of air leaving the intercooler (or air inlet to HPC) is held constant (30 °C), so the increase of LPC pressure ratio increases the heat removed by the cooling water, which is an overall system loss. Thus, the heat rejection from the cycle or loss to the environment increases when increasing LPC pressure ratio.
- Increasing the LPC pressure ratio decreases the HPC pressure ratio, since the overall pressure ratio is fixed. Since the temperature of air inlet to the HPC (or air outlet from intercooler) is held constant, the temperature of the HPC outlet decreases with increasing PLC pressure ratio, and thus reduces the expander inlet temperature. Less power is developed by the expanders as a result causing the system efficiency to decrease.

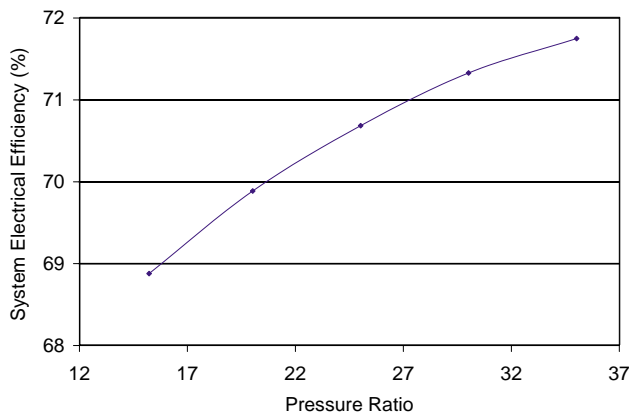


Fig. 4. Sensitivity of system efficiency to overall pressure ratio, $\pi_{LPC} = 4$, MC = 29%, EA = 80%.

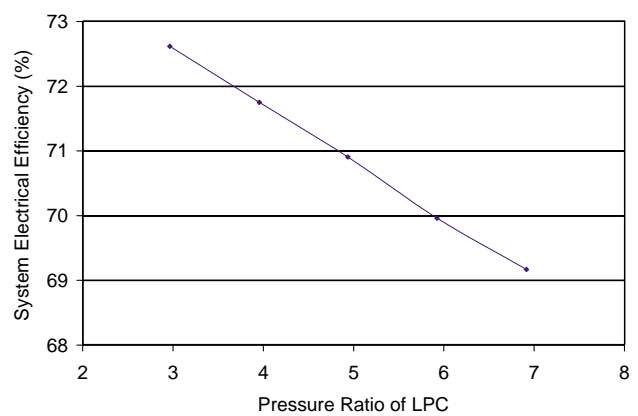


Fig. 5. Sensitivity of system efficiency to pressure ratio of LPC, $\pi_{overall} = 35$, MC = 27.6%, EA = 80%.

5. System optimization

Results presented in the parametric analyses of Figs. 2–5 suggest that reasonable efficiencies can be achieved with the SOFC–ICGT system configuration and that it is a promising cycle for meeting Vision 21 goals. To further understand SOFC–ICGT system performance and to reach the Vision 21 goals, the concurrent effects of parameters and of interactions amongst these parameters on the overall system performance were studied using a novel optimization process. A special analysis tool using a design of experiments (DOEx) approach was used to analyze the interactions of parameters, which are challenging to examine in a basic parametric analysis. The DOEx approach can also help optimize the results to choose the system operation design points [11].

The basic premise of DOEx is one of determining statistical significance of effects, removing of ineffectual parameters, and determining the interactions amongst a large number of parameters that may be important to overall performance using detailed statistical analyses of variance. Details of this approach can be found at Stat-Ease [11]. These approaches are typically applied to experimental parametric investigations. In the current optimization strategy, we propose to apply similar statistical analyses to simulation results where complex interactions and parametric effects must be determined to increase overall system efficiency.

5.1. Design list

The four design parameters listed in Table 2 were studied in the basic parametric analyses utilizing the DOEx approach. The electrical efficiency of the overall system was the only response that was considered in the design. More details about the DOEx approach in this work can be found in [12].

5.2. Parameter interaction analysis

Compared to the one-factor effect plot shown in basic parametric analysis, interaction plots can provide more details regarding the joint impacts of certain parametric variations (factor) on the system performance.

Fig. 6 illustrates the interactive effects of excess air and moisture content on system efficiency in the case where

Table 2
Design list

	Range
Factors	
Moisture content (%)	22–28
Excess air (%)	72–170
Overall pressure ratio	15–60
LPC pressure ratio	3–6
Response	
Efficiency (LHV) (%)	To be maximized

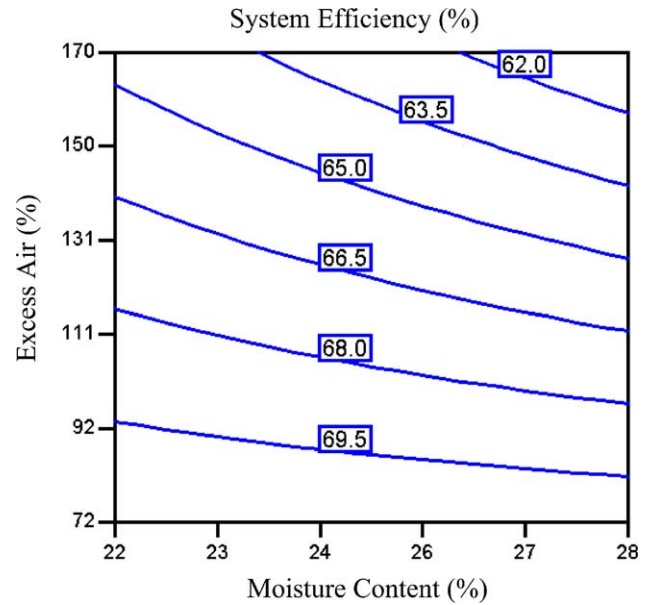


Fig. 6. Interactive effects of excess air and moisture content on efficiency, where $\pi_{LPC} = 4.5$, $\pi_{overall} = 37.5$.

overall pressure ratio and LPC pressure ratio are fixed. The system efficiency increases with the decrease in excess air, which is consistent with the results from one factor effect analysis on excess air (Fig. 3). Moreover, from the contours of Fig. 6, one can deduce that at higher excess air levels, the impact of moisture content on system efficiency is more significant than at lower excess air levels.

Fig. 7 shows that when overall pressure ratio and moisture content are kept constant, the highest system efficiency can be achieved when both excess air and LPC pressure ratio are

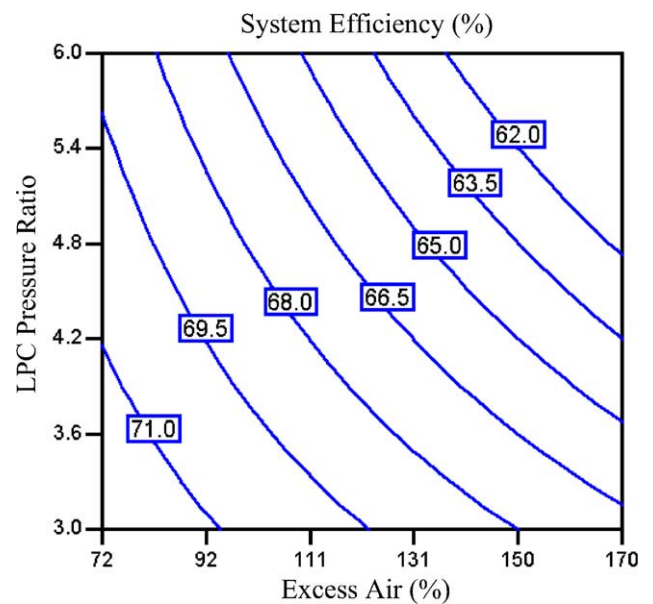


Fig. 7. Interactive effects of excess air and LPC pressure ratio on efficiency, where $\pi_{overall} = 37.5$, MC = 25%.

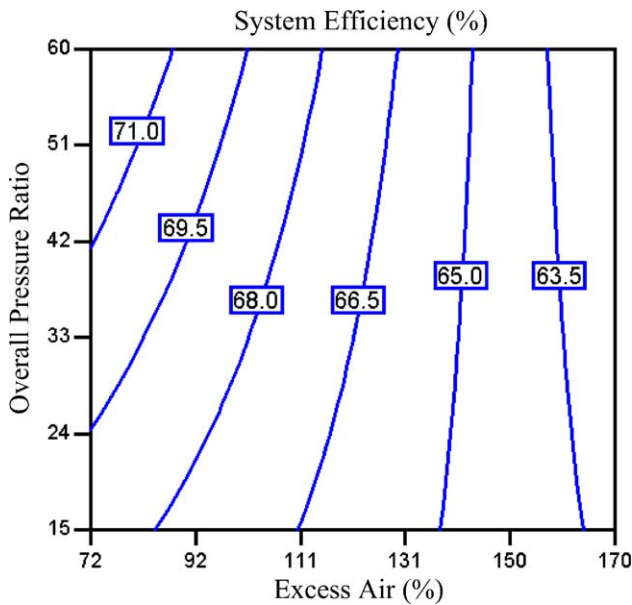


Fig. 8. Interactive effects of excess air and overall pressure ratio on efficiency, where $\pi_{LPC} = 4.5$, MC = 25%.

at their lowest levels. Also, when excess air is higher, the effect of LPC pressure ratio on system efficiency is much more significant. As discussed in the one factor effect analysis, higher LPC pressure ratios result in higher heat removal from the cycle by cooling water in the intercooler. When excess air increases, the air flow rate in the compressor increases (fuel flow rate is kept constant). As a result, the heat removed in the intercooler is higher, and therefore the decrease of the system efficiency is more significant. Notice that when the LPC pressure ratio is lower, then the operating temperature in the high pressure compressor is higher. HPC discharge temperature is about 480 °C when overall pressure ratio is 60 and LPC pressure ratio is 3. Therefore, the material requirements for the HPC as well as its cost are higher when lowering the LPC pressure ratio to achieve a higher overall system efficiency. Thus, the optimum pressure ratio for the LPC may be dictated by the design of the HPC materials and the HPC costs that the overall system can tolerate.

In Fig. 8, the overall pressure ratio is shown to have an obvious positive impact on the system efficiency when excess air is lower. However, the effect becomes negative when excess air becomes greater than 150% in this case. When excess air is low, the turbine inlet temperature is high (about 1000 °C when excess air is 72% and overall pressure ratio is 60). As a result, the increase of overall pressure ratio improves the gas turbine efficiency as well as the whole system efficiency, because of larger power generation in the turbine expansion process with higher pressure ratio and higher TIT. On the contrary, if excess air is higher, TIT becomes lower (about 700 °C when excess air is 170% and overall pressure ratio is 60). Thus, when excess air is too high, the gas turbine efficiency goes down due to more power being consumed

in compressors compared to the increase of the power produced in the expanders. As a result, increasing overall pressure ratio does not improve the system performance when excess air is relatively high.

5.3. Optimization

The interactions analyses and parameter modifications investigated using the DOE approach can be used to determine optimum system operation [11]. The optimization analyses performed using Stat-Ease show that the highest system efficiency can be achieved when the overall pressure ratio is high, excess air is low and the pressure ratio of the LPC is low.

Considering the complicated effect of moisture content on the system performance (see Fig. 2), some additional systems simulation work is conducted in order to determine the optimum design points. The range of moisture content investigated was set to from 25 to 34%. Excess air is set to 55%, the lowest value chosen for this study since the efficiency increases with decreased excess air; overall pressure ratio is set to 50 since the efficiency increases with increasing overall pressure ratio, and the LPC pressure ratio is set to three, the lowest value studied since the efficiency increases lower LPC pressure ratio. The results from simulation of the overall system of Fig. 1 under these conditions for a series of variations in moisture content are shown in Fig. 9. These results show that the highest efficiency can be achieved when the moisture content is around 32%. This is determined for conditions when the temperature difference between hot gas into the economizer and the water out of the economizer is held close to 35 °C.

Utilizing this optimum design, where moisture content is set at 32%, the system efficiency is calculated by APSAT to be 75.8%. The optimum design, thus determined, is summarized in Table 3. As stated previously, the supply pressure of the fuel is assumed to be 300 psia in this study. Considering that many of the pipelines transporting the large quantities of natural gas required by central station power plants operate at a pressure of 600–1000 psia (which is significantly higher than 50 bara), a fuel compressor is not necessarily required. Simulation of the system without a fuel compressor resulted in a calculated net system efficiency of 76.2%.

Table 3
Optimum design

Moisture content (%)	32
Excess air (%)	55
Pressure ratio	50
LPC pressure ratio	3
SOFC ac power (MW)	450
GT power (MW)	177
Total power (MW)	627
Electric efficiency (LHV) (%)	75.8

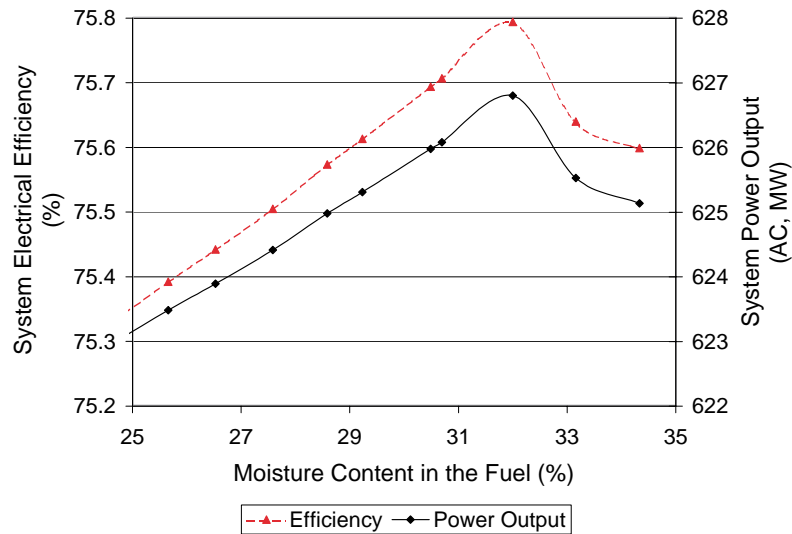


Fig. 9. Optimization: system efficiency and power output vs. moisture content.

6. Discussion and conclusions

Through analyses conducted using the APSAT computer code and from the novel optimization strategy using design of experiments, an optimum design for a solid oxide fuel cell and intercooled gas turbine hybrid cycle has been achieved. The electrical efficiency was shown to be as high as 75.8% based on natural gas lower heating value.

Some promising characteristics of the SOFC–ICGT cycle from the simulation results are:

- Increases in operating pressure increase overall system efficiency. However, the technical challenges in developing an SOFC with a very high operating pressure as well as the associated development costs will be high. So, there is a balance between the development cost and the efficiency. (In this work, the system efficiency was the only factor considered.)
- For a given overall compressor pressure ratio, a decrease in the LPC pressure ratio increases the overall system efficiency. At the same time, the operating temperature in the HPC and also the requirements for more exotic materials for HPC construction increase. A tradeoff between cost and efficiency is again required.
- Decreasing excess air in the SOFC has a positive effect on the overall efficiency.
- Moisture content in the fuel has a bimodal effect on the system performance. When increasing the moisture content of the fuel, the mass flow rate of working fluid in the expanders increases, while the inlet temperatures of the expanders decrease. Additionally, the moisture content in the fuel also affects the partial pressure of the reactants in the anode gas: the anode concentration and activation polarizations as well as the reforming process are all affected. As in previous parametric considerations, one must

trade-off practical concerns for carbon deposition against all of these impacts when considering the design point for moisture content.

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