Integrated Nuclear Power Generation Project

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Abstract

The development of nuclear energy technologies involves multiple research fields, including reactor design and licensing issues. In the modern world, interests had increased in methods to integrate nuclear reactors with other applications such as renewable energy, desalination and low-carbon electricity sources into the grid. In addition to nuclear energy itself, there are technical challenges and business contexts we need to take into consideration. Usually, traditional nuclear reactors are limited to base load electricity generation. In our project, the pebble-bed fluoride-salt high-temperature reactor (PB-FHR) could have the flexibility to meet both the base load and peak load.

To optimize the PB-FHR design to fit into the energy industry, we performed an energy market forecast and financial modeling based on the assumptions as well as market analysis we derive from the previous research and findings. This project assesses not just the capability of the reactor technology but also the potential business opportunity of the integration. On the technology side, our work is focused on the optimization of reactor design, integration with other energy sources and application of desalination. Based on these technologies in hand, we develop a comprehensive development and deployment plan forecasting the energy demand and revenue generation in California. This plan is mainly focused on the flexible nuclear generation capacity that is able to cope with the fluctuation of market demands and provide other grid services such as integration with wind and solar sources to meet multiple needs in the energy industry.

1. Introduction

1.1 Objective & Scope

This project addresses the optimization of pebble-bed fluoride-salt high-temperature reactor (PB-FHR), desalination process of reverse osmosis mechanism, regulatory issues and policies, simplified financial modeling of the energy market in California and analysis of peak load, desalination and gas turbine based on the control system of nuclear power plant. This report presents an analysis of the optimized control system for gas turbines to be capable of providing the energy services and its potential integration with PB-FHR.

The scope this report addresses is mainly focused on the context of the San Onofre Nuclear Generating Station (SONGS) location, and the potential to develop new reactors at this site. In terms of the previous data of traditional nuclear reactors in SONGS [1], PB-FHR stands out with its power efficiency, capacity to desalinate water with its waste heat and small-module-based which is able to scale with multiple units in order to provide peaking power. In addition to the advantages the reactor itself, this work also analyzes the role the control system plays in the gas turbine, reactor, power plant and market.

1.2 Business Context of Nuclear Industry

One of the most critical components of power plant to provide services is transmission. In California, the California Independent System Operator (CAISO) manages the electricity transmission infrastructure, determines which power plants bring electricity into the system, and how it is distributed where needed. Based on the CAISO standards, PB-FHR is able to not only meet the ancillary services [2] but also has the capacity to provide additional applications. Control system is capable of meeting the fluctuation of the market demand by its feedback controller to tune the power generation rate.

Moreover, the design of the control system in gas turbine is supposed to provide the services in peak load dispatching power station, cogeneration of heat and power, black-grid restart, etc. In order to multifunction reliably, there are certain requirements gas turbine needs to meet, such that high efficiency, high reliability, long lifetime, low noise, light weight, small volume, low pollution and capacity to be expanded. Clearly, they are the features PB-FHR has in common with. Following sections will introduce how the control system plays in gas turbine and the compatibility with PB-FHR to perform the services and applications with the advantages of PB-FHR. The work also applies the theory of the control system in gas turbine to cogeneration of natural gas and nuclear power. In this case, PB-FHR, our targeted nuclear reactor integrated with gas turbine is able to meet the peaking demand. On the other hand, integration with desalination plants could generate water with potentially lower cost than other traditional desalination models.

2. Literature Review

2.1 Background

In the current world, the need for new, low-carbon energy sources is critical. The regulation on energy sources also becomes stricter like regulating the emission of the carbon dioxide. In the U.S. for example, the Fig. 1 shows the balance of demand and supply is not even. To fix the imbalance, turning to other efficient energy resources is on its way. Advanced designed nuclear reactor like PB-FHR has the potential to serve as a stable electricity supply; meanwhile, there are some other extended applications that could produce multiple benefits.

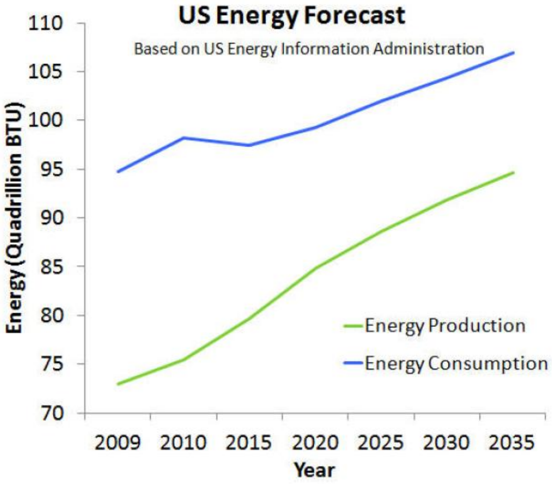


Fig. 1. U.S. Energy Forecast [3]

Another issue the reactor has the potential to address is the water scarcity in California, as shown in Fig. 2. Integrating the nuclear power plants with desalination technology could create the product portfolio of electricity and water. With better power efficiency and the remarkable waste heat, the model is worth putting into practice.

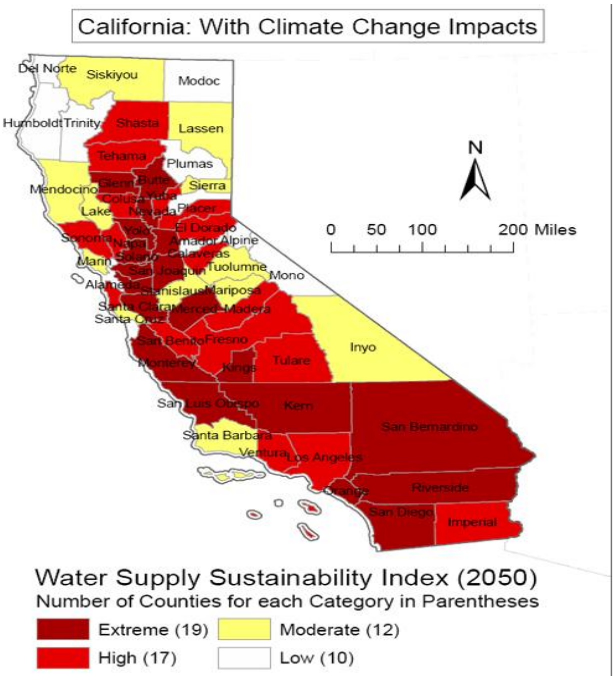


Fig. 2. Unsustainable Water Consumption in California [4]

2.2 System Configuration & Optimization

Currently, the nuclear reactor technology developers are studying Generation IV, still necessary to be tested and verified before entering the market. A potential design is the PB-FHR, operating at high temperature, 600℃ to 700℃, and low pressure, 1 atm [5], which facilitates the thermo-chemical production of hydrogen and the production of electricity [6]. In the meanwhile, the low-pressure molten-salt coolant, with its high heat capacity and natural circulation heat transfer capability, creates the potential for robust safety, including fully passive decay-heat removal, and improved economics with passive safety systems that allow higher power densities [5].

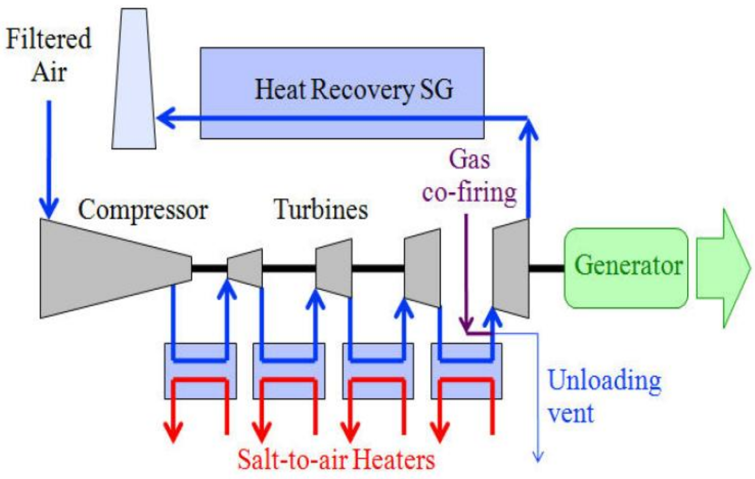


Fig. 3. Nuclear Open Air Brayton Combined Cycle (NACC)

Moreover, the high operating temperature facilitates one of the most crucial components of the integration system, the nuclear open air Brayton combined cycle (NACC), briefly explained in Fig. 3. [5]. NACC power conversion enhances the thermal efficiency by 5 to 6% [6] and recovers the heat for the additional electricity or cogeneration (co-fire with natural gas).

Current desalination technologies could be categorized into four major categories, Multi Stage Flash (MSF), Multi Effect Distillation (MED), Reverse Osmosis (RO) and Vapor Compression (VC). In terms of costs and the efficiency, MED integrated with Brayton cycles could compete with RO [7]. These two systems to desalinate water are the most doable ways which this project draws upon.

3. Methodology

3.1 General Methods (Team)

The grid integrated nuclear power generation team is researching the topics of thermodynamics of our nuclear reactor (PB-FHR), reverse osmosis method of desalination, optimization of the control system in gas turbine and financial modeling of water and electricity in California.

Thermodynamics simulation is done by a software tool, Thermoflex. Reverse osmosis is one of the most efficient desalination processes in terms of costs and technology complexity [8]. Optimization of the control system in gas turbine is done by the block diagram to tune different controllers. Then, verify the concept based on the research papers for justification. Financial modeling of electricity is based on the comprehensive data in CAISO Open Access Same-Time Information System (OASIS) website [9].

3.2 Optimization by References

The configuration of the control system in gas turbine consists of four blocks: speed/load control, temperature control, fuel control and air control [10] shown in Fig. 4.

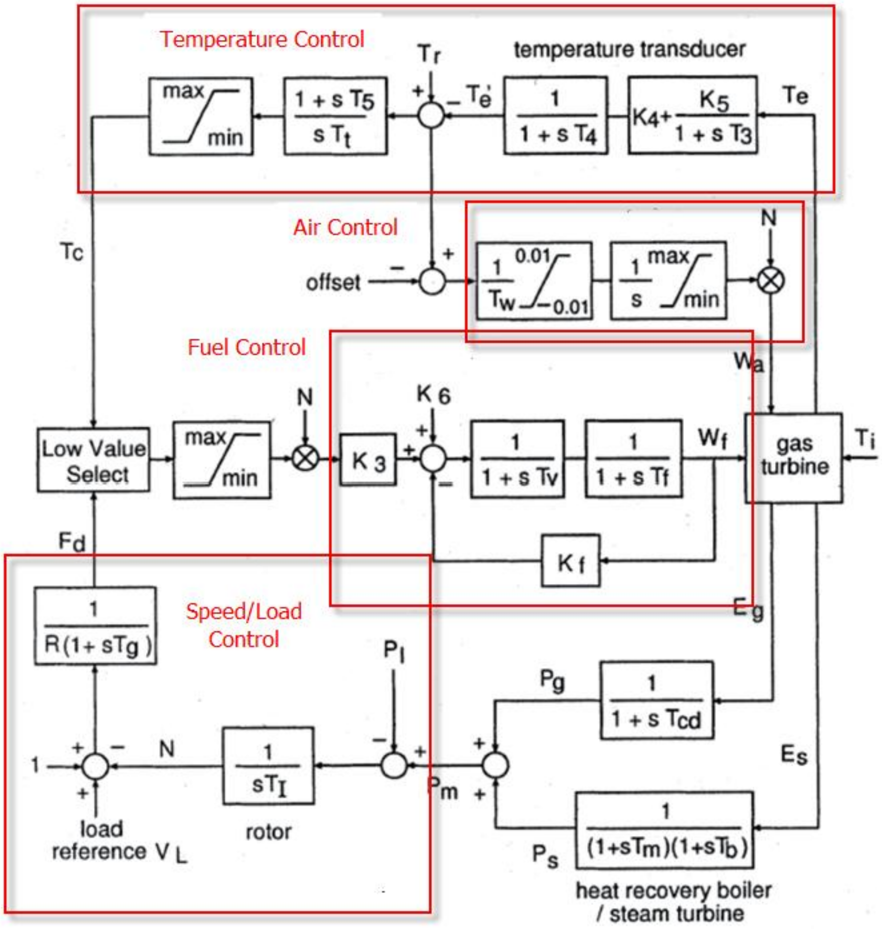


Fig. 4. Model of Combined Cycle Power Plant [10]

These four blocks are the key components to model the control system. Speed/load control determines the fuel demand according to the load reference and the rotor speed deviation. Temperature control restricts the exhaust temperature not to injure the gas turbine. The exhaust temperature is the temperature control signal to the system and is compared with the reference temperature. Fuel control is connected to the temperature control system by the temperature control signal. Control signal is positive dependent on the demand of the fuel. Air control block adjusts the air flow through the compressor inlet guide vanes (IGV)[11], which directs the air onto the compressor at the correct angle, so as to attain the desired exhaust temperature. The optimization analysis is focused on the four different types of control system and I will analyze them individually in the following sections.

4. Discussion

4.0 Overview

In the discussion, the goal is to qualitatively analyze the potential applicability of the integration of gas turbines (GT) and PB-FHR to perform certain applications like the desalination and cogeneration. Firstly, the option of a variety of fuel cells to supply GTs goes to Solid Oxide Fuel Cell (SOFC). SOFC and GT hybrid systems are recognized to be very efficient power plants with negligible emissions which is environmental-friendly [12]. To be integrated with promising desalination technologies, there are benefits to be proposed currently. For MED, Hosseini, M., et al. [13] indicated the fuel stack pressure could enhance the system power and distilled water capacity. For RO, GeorgeChittu, K., et al. [14] also introduced the high efficiency and larger capacity of the water could be generated by FCs.

Consistent with the PB-FHR system, Rankine and NACC cycles could also be used in SOFC and GT hybrid system. Zabihian, F., et al. [15] and Akkaya, VA., et al. [16] proved Rankine cycle could improve the efficiency of SOFC systems by around 20%. Kobayashi, Y., et al. [17] proposed triple combined-cycle system that integrated steam turbine (ST), GT and SOFC based on the Brayton-Rankine combined cycle to further enhance the power generation efficiency up to 70%. These literature reviews gave us a picture that if the SOFC & GT hybrid system and its capital costs could be optimized and reduced by a considerable amount respectively, the integration with PB-FHR to perform desalination services would be pragmatic.

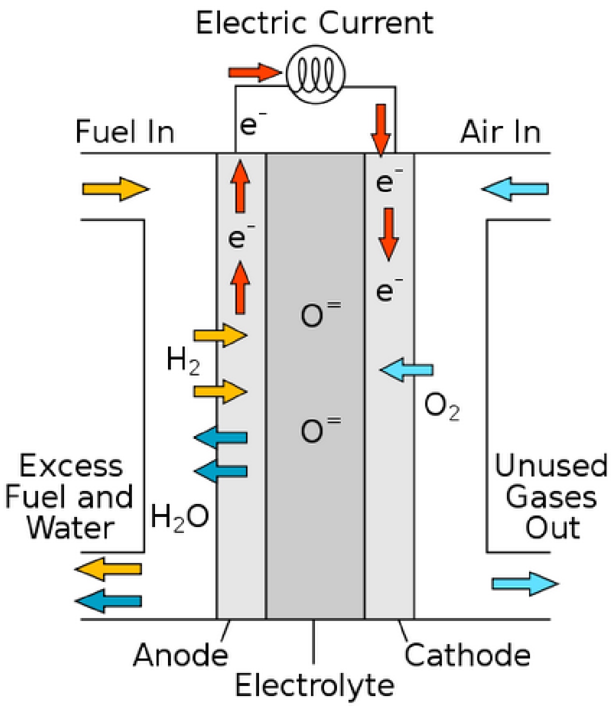


Fig. 5. Diagram of SOFC [18]

4.1 Solid Oxide Fuel Cell (SOFC) & Gas Turbine (GT) Hybrid System

SOFC is an electrochemical conversion device that produces electricity directly from oxidizing a fuel. The basic diagram is shown in Fig. 5. The important strengths of the SOFC that make the industry likely to adopt in the gas turbine are high conversion efficiency, long-term stability, fuel flexibility, low carbon emissions and relatively low costs. The integration of a gas turbine and fuel cell is potentially promising for our co-fire system with natural gases or other biomass fuels [19] and desalination plants no matter what the thermal-driven process (MED) or pressurized-driven process (RO) is. It is because the system not only provides an amount of exhaust high-temperature gases but also the electricity by favorable conversion efficiency. This technology is one of the major ongoing R&D activities [20, 21] and the focus of the development includes achieving the higher electric efficiency, reducing power plant costs, and increasing the system capacity for generation of the power.

4.2 Speed & Load Control

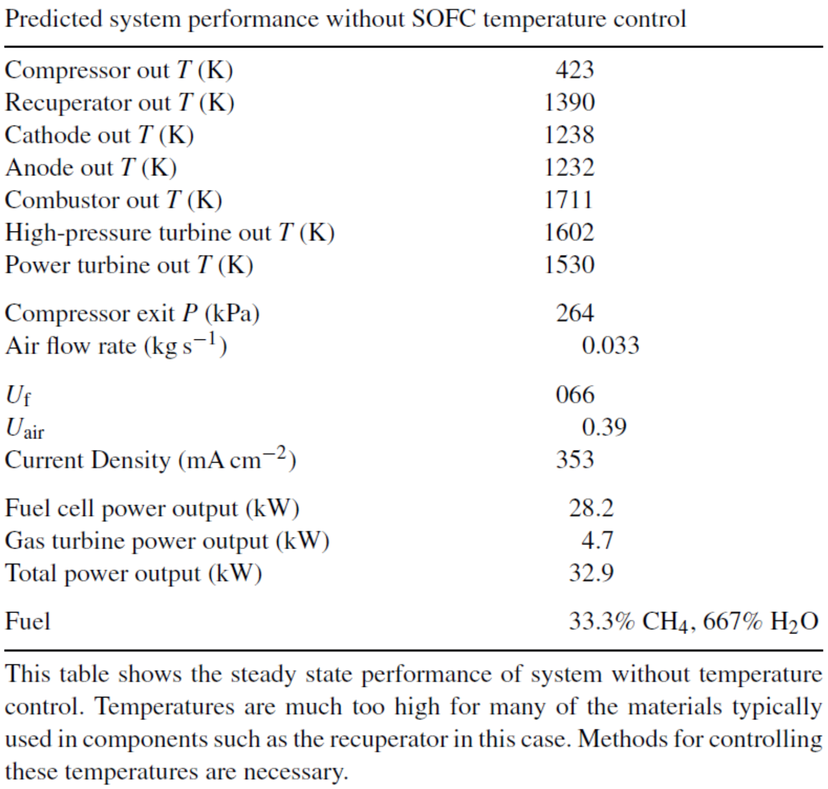
In the system of speed and load, the optimized control strategy is variable speed [22] and part-load operations [23]. On the speed side, the work of Roberts, R., et al. [22] compared the fixed and variable speed operations. For fixed speed operation, the large scale (MW) gas turbine with synchronous generators and other micro-turbine generators are designed to operate at a constant speed. Since the GT is operating at constant speed, the compressor air mass flow cannot be manipulated. In this case, the constant speed results in excess air mass flow (higher air-to-fuel ratio) when the power demand is low. It further causes the low operating temperature for the SOFC and the fuel cell voltage increases as the load demand decreases because of lower polarization and resistive losses. These two consequences reduce the efficiency due to less heat generated indicated by the same air-to-fuel ratio under the low demand. On the contrary, the variable speed operation could fix the problem by tuning the air-to-fuel ratio dependent on the fluctuation of the demand. Specifically, reduce the air mass flow when the demand is decreasing. The efficiency of the variable versus fixed speed is 66% to 53% [22].

On the load side, the demand in the energy market fluctuates on a daily basis. It is more appropriate to operate the GT in part-load mode rather than the full-load. In part-load, the control modes could be categorized into three systems, fuel-only, rotational speed (variable speed) and variable inlet guide vane (VIGV) control, which varies the air-entering area of the compressor inlet by changing the angles [23]. VIGV control is not discussed here and it is more suitable for large-module-base reactors which are not PB-FHR. Fuel-only control maintains a constant air supply which reduces the efficiency at the low demand discussed in the speed control. While rotational speed control system not only meets the fluctuation of the demand with the highest efficiency of the three systems but also maintains the same turbine inlet temperature which enhances the stability.

4.3 Temperature Control

Temperature control is a crucial part in the integration of PB-FHR and GT. High operating temperature in both PB-FHR and SOFC of GT hybrid system is highly favorable. However, the higher the temperature, the more unstable the system is, especially in GT. Kaneko, T., et al [19] introduced the control strategy of the power and temperature in terms of the biomass. This work indicated the instability occurs due to the fluctuation of gas composition in the fuel which implies the cogeneration system of the natural gas may have the same issue to address.

As the Fig. 6. shows the temperature of combustor exit is over 1700 K. This high temperature is not tolerable either by metal or ceramic blades. Besides that, high SOFC operating temperature causes Nernst potential (reverse potential) to drop, leading to a drop in fuel utilization. As fuel utilization drops, more fuel goes to the combustor, creating an even higher combustor exit temperature, eventually increasing the power turbine exit temperature. To be specific, the fuel utilization and current density [19] are lower without the temperature control which deteriorates the stability and efficiency.



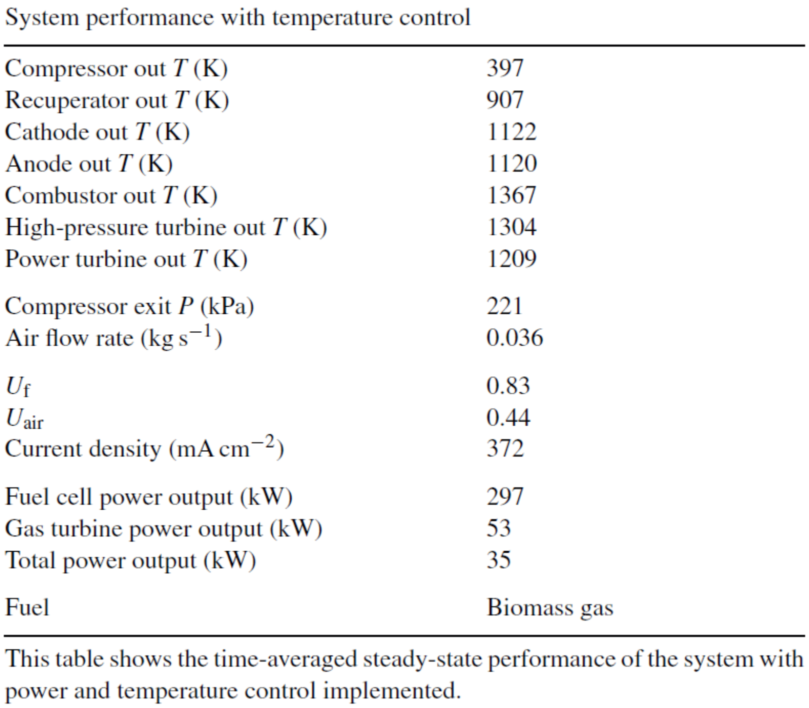
Predicted system performance without SOFC temperature control

Compressor out T (K)	423
Recuperator out T (K)	1390
Cathode out T (K)	1238
Anode out T (K)	1232
Combustor out T (K)	1711
High-pressure turbine out T (K)	1602
Power turbine out T (K)	1530
Compressor exit P (kPa)	264
Air flow rate ($\mathrm{kg\,s^{-1}}$)	0.033
U_f	066
U_{air}	0.39
Current Density ($\mathrm{mA\,cm^{-2}}$)	353
Fuel cell power output (kW)	28.2
Gas turbine power output (kW)	4.7
Total power output (kW)	32.9
Fuel	33.3% CH_4, 667% H_2O

This table shows the steady state performance of system without temperature control. Temperatures are much too high for many of the materials typically used in components such as the recuperator in this case. Methods for controlling these temperatures are necessary.

Fig. 6. Table of the Performance without Temperature Control [19]

One way that Kaneko, T., et al [19] introduced to control system temperature is to import an amount of bypass flow of exhaust that preheats the inlet air to the SOFC. In this case, the system can avoid this kind of self-exciting temperature rise by controlling the temperature of air going into the SOFC. The amount of gas bypassing that preheats the inlet air can be controlled by a valve. The results with this control are shown in Fig. 7. Even this combustor exit temperature, 1367 K, is still pretty high need to be put into experiment to test the tolerance of the system. Pomeroy, M. J., [24] provided some ways to strengthen the GT materials in terms of coatings. In general, the higher the operating temperature, the higher the material and manufacturing costs.



System performance with temperature control

Compressor out T (K)	397
Recuperator out T (K)	907
Cathode out T (K)	1122
Anode out T (K)	1120
Combustor out T (K)	1367
High-pressure turbine out T (K)	1304
Power turbine out T (K)	1209
Compressor exit P (kPa)	221
Air flow rate (kg s^{-1})	0.036
U_f	0.83
U_{air}	0.44
Current density (mA cm^{-2})	372
Fuel cell power output (kW)	297
Gas turbine power output (kW)	53
Total power output (kW)	35
Fuel	Biomass gas

This table shows the time-averaged steady-state performance of the system with power and temperature control implemented.

Fig. 7. Table of the Performance with Temperature Control [19]

4.4 Fuel Control

Fuel control is related to the utilization of the fuel and the portion of the oxygen to oxidize the fuel in the system. The work of Calise, F., et al. [25] introduced the strategy to deal with the fuel control in terms of the parameters, fuel utilization factor (U_f) and fuel-to-oxygen ratio (FO). The target is to maintain U_f at the highest level which is not possible due to technological and economic constraints. The major advantage of the high U_f is the high electrochemical rate of reaction leading to the raise of its chemical exergy destruction rate. Thus, the higher the $\mathrm{U_f}$, the higher the electrical efficiency.

The air inlet mass flow rate of the hybrid SOFC-GT system depends on the electrochemical rate of reaction, cell temperature and combustion reaction. These reactions and parameters have direct impact on the rate of the fuel utilization. The amount of oxygen required to oxidize hydrogen in the SOFC and other fuels in the turbine is expected to keep at reasonable values so as to maintain the operating temperature and pressure. By and large, the higher the FO is, the higher electrical efficiency the GT has. However, the FO could not be increased arbitrarily since the limitation of the temperature in terms of the cost of the material.

4.5 Air Control

Air control is more like the combination of the load, temperature and fuel control. As discussed in the load control section, the variation of the air-to-fuel ratio under the fluctuation of the demand determines the system efficiency. In terms of temperature, air feed temperature has a big influence on the cell performance due to a relatively large fuel flow [26]. To optimize the feed temperature (maximum efficiency), there are parameters need to be taken into consideration, solid temperature, fuel utilization and energy required for preheating the feed gases.

Calise, F., et al. [25] indicated that steam-to-carbon (SC) ratio is another parameter that determines the plant thermal efficiency. The lower the SC is, the lower the amount of heat required by the heat recovery steam generator, which supplies the steam to support the internal reforming reaction [27], causing the higher thermal efficiency. However, the minimum value of the SC constrained by the technological limitations of the SOFCs.

4.6 Results

Based on Stiller, C., et al.[28], it introduced the strategy to control SOFC-GT hybrid system. Fig. 8. is the layout of the hybrid system where I plugged SOFC in our PB-FHR system for simulation. The system is under 900°C and there are three types of output power and heat, PB-FHR, heating air from the SOFC and the SOFC chemical reaction denoted by (P_{FHR}, Q_{FHR}), (P_{air}, Q_{air}) and (P_{SOFC}, Q_{SOFC}) respectively.

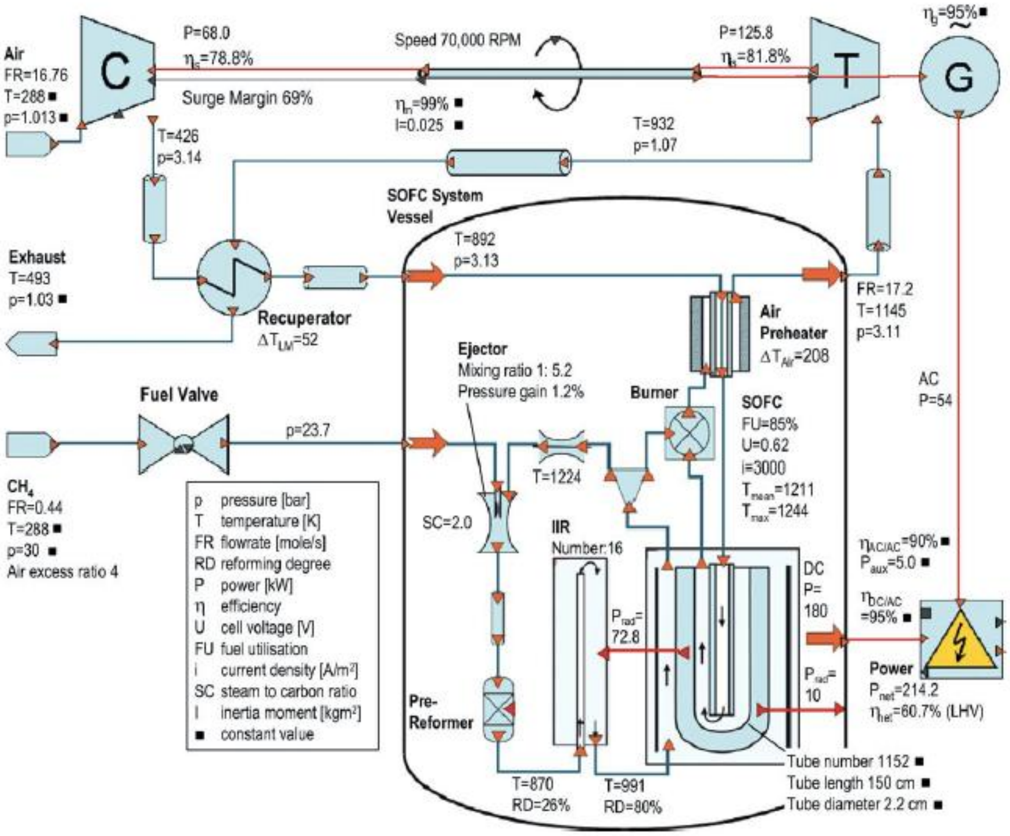


Fig. 8. Hybrid Cycle Layout and Design Point Values [28]

Since the scale of the PB-FHR is different from that of the SOFC-GT hybrid system, I need to scale from analogy. Data from Professor Per Peterson's group, PB-FHR and GT system without SOFC generates the table in Fig. 9.

$\mathrm{P_{net}} = 175.84\mathrm{MW}$ $\mathrm{Q_{net}} = 383.93\mathrm{MW}$ $\eta_{\mathrm{net}} = 45.8\%$
$\mathrm{P_{FHR}} = 107.61\mathrm{MW}$ $\mathrm{Q_{FHR}} = 263.93\mathrm{MW}$ $\eta_{\mathrm{net}} = 40.76\%$

Fig. 9. Data of PB-FHR & GT from Prof. Per Peterson's Group at UC Berkeley

From Fig. 9., PB-FHR & SOFC-GT hybrid system could be scaled to observe the corresponding efficiency and its power generation shown in Fig. 10. As observed, 52.97% is the overall efficiency which is larger than 45.8% derived from the original system. Moreover, this data is based on the same heat that both system could produce. As a matter of fact, the SOFC-GT system could generate much more heat than the original system so that the efficiency is underestimated. That way, I could infer the actual efficiency is far beyond 52.97%.

	Data from [28]	Original PBFHR-GT	PBFHR-SOFC-GT
$\mathrm{P_{air}} + \mathrm{P_{SOFC}}$	214.2kW	68.24MW	$68.24 + 184.65$ $= 252.89\mathrm{MW}$
$\mathrm{P_{FHR}}$	X	107.61MW	107.61MW
$\mathrm{Q_{FHR}}$	X	263.93MW	263.93MW
$\mathrm{Q_{air}} + \mathrm{Q_{SOFC}}$	352.88kW	120MW	$120 + 296.62$ $= 416.62\mathrm{MW}$
η_{net}	$(\mathrm{P_{FHR}} + \mathrm{P_{air}} + \mathrm{P_{SOFC}})/\,(\mathrm{Q_{FHR}} + \mathrm{Q_{air}} + \mathrm{Q_{SOFC}}) = 52.97\%$		

Fig. 10. Scaled Data from [28] & Fig. 9

5. Conclusion

The SOFC-GT hybrid system has a potential for high efficiency electricity production with low emissions. Its high operating temperature, combined cycles in GTs and other features are matched with PB-FHR allowing the potential compatibility. Additionally, the significant drawback of traditional desalination technology is the high power consumption and environmental impact due to the large electricity load. In this case, cogeneration technique is able to mitigate these consequences with more environmental-friendly and efficient fuel cell (SOFC) as well as the waste heat recycling (NACC) to enlarge the capacity of desalination plants. Flexible scalability (tuning) of this system is also favorable for being integrated into the nuclear power generation grid in order to adjust the output of plants. Overall, the most remarkable advantages of the SOFC and GT hybrid system to the desalination are the high efficiency, fuel utilization and the optimization of the costs to desalinate water.

In spite of those optimizations discussed in the previous section, technological and economic challenges still remain. For instance, the SOFC and PB-FHR favors the higher operating temperature; however, the lower operating temperature introduces more not only the flexibility in the hybrid configuration and design, but also the stability of materials used in SOFCs which widens the range of suitable materials. In the perspective of the part-load operation, even though the efficiency has been proven to be high, the part-load behavior of the system implies the unstable regimes (no steady-state exists). In addition to the constraints of the GT, the proven feasibility and risk analysis of PB-FHR are still on the way. Both the SOFC-GT hybrid system and PB-FHR are haven't been proven comprehensively profitable in the business context. This report provides qualitatively analysis and energy efficiency incentive but still lacks enough justification of an economic feasibility and numerical modeling of each control block.

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