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DESIGN AND PERFORMANCE ANALYSIS OF A SOLID OXIDE FUEL CELL / GAS TURBINE (SOFC/GT) HYBRID SYSTEM USED IN COMBINED COOLING HEATING AND POWER SYSTEM

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ABSTRACT

With high efficiency and very low emissions, fuel cells have been one of the choices of research in current energy development. The Solid Oxide Fuel Cell (SOFC) is a high temperature type fuel cell. It has the characteristic of very high operating temperature 1,027℃ (1,300K). The SOFC has the main advantage of very high performance efficiency (over 50%), but also has very high exhaust temperature. Current studies point out that the combination of SOFC and Gas Turbine (GT) can produce efficiency more than 60%. The exhaust temperature of this hybrid power system can be as high as 227 - 327℃ (500 - 600K). With this waste heat utilized, we can further improve the overall efficiency of the system.

A simulation program of SOFC/GT system and the introduction of the concept of Combined Cooling, Heating, and Power System (CCHP) have been used in this study. The waste heat of SOFC/GT hybrid power generation system was used as the heat source to drive an Absorption Refrigeration System (ARS) for cooling. This waste heat enables the SOFC/GT to generate electricity in the system while providing additional cooling and heating capacity. Therefore, we have a combined CCHP system developed using three major modules which are SOFC, GT, and ARS modules. The SOFC module was verified by our test data. The GT and SOFC/GT modules were compared to a commercial code and literature data. Both the single- and double- effect ARS modules were verified with available literature results. Finally, the CCHP analysis simulation system, which combines SOFC, GT, and ARS, has been completed. With this CCHP configuration system, the fuel usability of the system by our definition could be above 100%, especially for the double effect ARS. This analysis system has demonstrated to be a useful tool for future CCHP designs with SOFC/GT systems.

Keywords: solid oxide fuel cell, micro gas turbine, absorption refrigeration system, combined cooling heating and power system

NOMENCLATURE

ARS	Absorption Refrigeration System
A_s	Cross-sectional area of the flow channel
CCHP	Combined Cooling, Heating, and Power System
Ea	Activation energy (82kJ/mol)
GT	Gas Turbine
h_f	Anode flow channel height
k_0	Proportionality constant
LHV	Low heating value (kJ/kg)
n_{an}^i	Total anode inlet molar flow rate
P_{an}	Anode pressure
R_C	The cooling ratio
SOFC	The Solid Oxide Fuel Cell
Greek Symbols	
	Compressor efficiency (%)
$\eta_{cooling}$	Cooling efficiency (%)
η_e	Electric efficiency (%)
η_{fuel}	Fuel efficiency (%)
η_{HX}	The efficiency of the heat exchanger (%)
$\eta_{heating}$	Heating efficiency (%)
η_T	The turbine efficiency (%)

INTRODUCTION

Today, large-scale and high-efficiency power generation technology is facing two major issues, including energy depletion and environmental protection. The depletion of the global fossil energy in recent years results in the soaring of energy prices. With the "Kyoto Protocol" in 2005 and the Copenhagen carbon reduction agreements in 2009 coming into effect, saving power energy, improving power generation efficiency, and reducing carbon dioxide emissions have become the main issues in today's energy field.

Coal and oil are now the most used fossil energy in the world. With the rising oil and coal prices in recent years, the energy market is facing the new challenge on how to develop the next generation power technology to ease the fossil energy crisis. According to the US Department of Energy, the new generation power technologies must meet two requirements. First, it must be a new energy conversion method and secondly, it must have higher technology advantages over the existing technology, including distributed generation, high-capacity, high security, low NO_X, and other emissions. It appears that the CCHP and SOFC/GT systems are consistent with the above requirements and have considerable potential to become the next generation energy technology.CCHP has been the trend for distributed generation technology, which possesses good features of high energy efficiency, small environmental impacts, reliability, and economic benefits. Unlike traditional centralized power supply grid with losses, CCHP is distributed in the client's local reachable system.

This study of SOFC/GT hybrid power generation system with absorption refrigeration is conducted by combining a SOFC/GT hybrid module and an absorption refrigeration system module (ARS). Then the system is used to study the performance characteristics of a CCHP system with optimized configuration analyses. The ARS modules with single- and double-effect studies are also considered.

SYSTEM INTRODUCTION

There are three modules in this study: SOFC, GT, and the ARS. The SOFC/GT hybrid module has been studied in the past. However, there are few research papers related to SOFC/GT combined with ARS for CCHP system study.

1. Solid Oxide Fuel Cell (SOFC)

A solid oxide fuel cell (SOFC) is an electrochemical conversion device that produces electricity directly from oxidizing a fuel. Advantages of SOFC fuel cells include high efficiency, long-term stability, fuel flexibility, low emissions, and relatively low cost. Usually it has a tubular or a planar design, which is used in this study. The planar design is predicted to have higher energy density and can be modular packaged. Hundreds of these cells are then connected in series to form what most people refer to as an "SOFC stack". The basic structure of a planar design SOFC is shown in Figure 1.

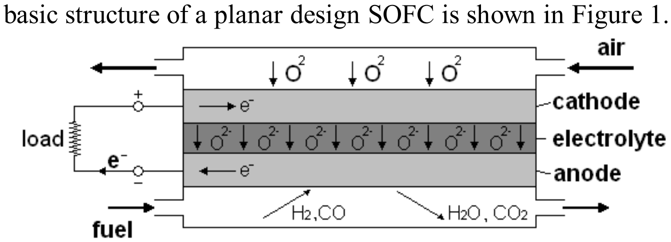


Figure 1. Solid Oxide Fuel Cell (SOFC)

The solid-state electrolyte is of oxygen ion conductivity ceramic material, using hydrogen as the main fuel. Because of these high temperatures, light hydrocarbon fuels, such as methane, propane and butane can be internally reformed within the anode. SOFC converts chemical energy into electrical energy directly. Theoretical efficiency of a SOFC device can reach up to 60%. The higher operating temperature makes SOFC suitable candidates for application with gas turbine engine energy recovery devices or combined heat and power, which further increases overall fuel efficiency.

2. Gas Turbine (GT)

As shown in Figure 2, air enters the compressor, and discharging from the compressor, flows through a diffuser. Then the air is directed to the regenerator/recuperator covers at the sides of the engine. The compressor discharge air then flows inward through the regenerator/recuperator to the combustor. The gases from the combustor expand first through the gasifier turbine and then through the power turbine. The power turbine usually has a variable nozzle guide vane with different setting angles representing different engine operating lines. After expansion through the power turbine, the gases are

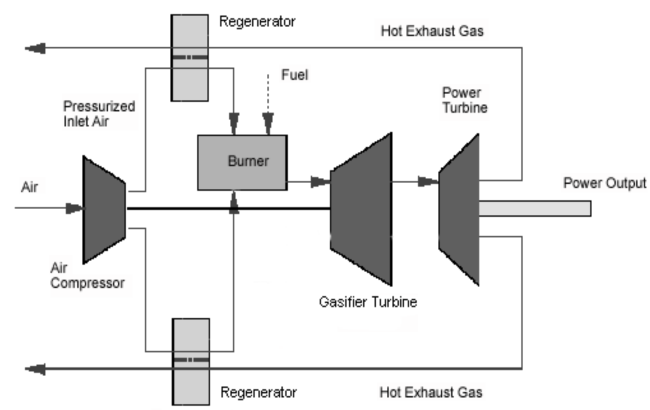


Figure 2. Gas Turbine Operation Principle (Twin-Shaft Machine)

3. Absorption Refrigeration System (ARS)

Absorption refrigeration systems (ARS) are quite similar to traditional compression refrigeration systems. In ARS, an absorber, generator, pump and recuperative heat exchanger replace the compressor. Like mechanical refrigeration, the cycle begins when high-pressure liquid refrigerant from the condenser passes through a metering device into the lower-pressure evaporator and collects in the evaporator sump. The transfer of heat from the comparatively warm system water to the now-cool refrigerant causes the latter to evaporate, and the resulting refrigerant vapor migrates to the lower-pressure absorber. There, it is soaked up by an absorbent lithium-bromide solution. This process not only creates a low-pressure area that draws a continuous flow of refrigerant vapor from the evaporator to the absorber, but also causes the vapor to condense as it releases the heat of vaporization picked up in the evaporator. This heat is transferred to the cooling water and released in the cooling tower.

To sustain the refrigeration cycle, the solution must be reconcentrated. This is accomplished by constantly pumping dilute solution from the absorber to the generator, where the addition of heat boils the refrigerant from the absorbent. Once the refrigerant is removed, the reconcentrated lithium-bromide solution returns to the absorber, ready to resume the absorption process. Meanwhile, the refrigerant vapor liberated in the generator migrates to the cooler condenser. There, the refrigerant returns to its liquid state as the cooling water picks up the heat of vaporization carried by the vapor. The liquid refrigerant completes the cycle returning to the metering device.

4. SOFC/GT Hybrid System

Since the SOFC stack operates at 1000°C, it produces a high temperature exhaust gas. If operated at an elevated pressure, the exhaust becomes a hot pressurized gas flow that can be used to drive a turbine. If a SOFC is pressurized and integrated with a gas turbine, the pressurized air needed by the SOFC can be provided by the gas turbine's compressor, the SOFC can act as the system combustor, and the exhaust from the SOFC can drive the compressor and a separate generator. This yields a dry (no steam) hybrid-cycle power system that promotes unprecedented electrical generation efficiency.

During normal operation of the pressurized SOFC hybrid, air enters the compressor and is compressed to ~3 atmospheres. This compressed air passes through the recuperator where it is preheated and then enters the SOFC. Pressurized fuel from the fuel pump also enters the SOFC and the electrochemical reactions takes place along the cells. The hot pressurized exhaust leaves the SOFC and goes directly to the expander section of the gas turbine, which drives both the compressor and the generator. The gases from the expander pass into the recuperator and then are exhausted. At ~200°C the exhaust is hot enough to make hot water. Electric power is thus generated by the SOFC (DC) and the generator (AC) using the same fuel/air flow. Analysis indicates that with such SOFC/GT hybrids an electrical efficiency of 55% can be achieved at power plant capacities as low as 250 kW, and ~60% as low as 1 MW using small gas turbines. At the 2 to 3 MW capacity level with larger, more sophisticated gas turbines, analysis indicates that electrical efficiencies of up to 70% are possible.

5. CCHP System

A Combined Heat and Power (CHP) system is to utilize the exhaust heat discharged by the power plant after generating electricity. Therefore, it can generate both electricity and heat. SOFC / GT hybrid system is considered one of the CHP systems.

In addition to CHP, the SOFC / GT hybrid system can also supply the needs for heating and cooling while producing electricity. Such energy utilization system is called the Combined Cooling, Heating, and Power System (CCHP) system. Currently, CCHP systems mainly incorporate gas turbines or internal combustion engines (IC). The SOFC / GT hybrid system has the advantage over GT or IC engines with efficiency up to 45%. With the exhaust temperature up to 600K, the SOFC / GT hybrid system can be a perfect candidate for heating and cooling combined generation. Therefore, the SOFC / GT hybrid system is considered ideal for CCHP, especially for distributed CCHP systems.

SYSTEM ANALYSIS

The CCHP system can be divided into SOFC, GT and ARS modules. These three modules can further be categorized into various components, as shown in Figure 3.

The SOFC module includes external reformer, SOFC stack, pump, compressor, heat recovery steam generator (HRSG), heat exchanger, and burner components. The GT module has compressor, turbine, heat exchanger (recuperator), and burner components. The ARS module is mainly composed of a number of heat exchangers (generator, absorber, condenser, and evaporator), pump, expansion valve and other components. The working fluid for ARS is LiBr Solution.

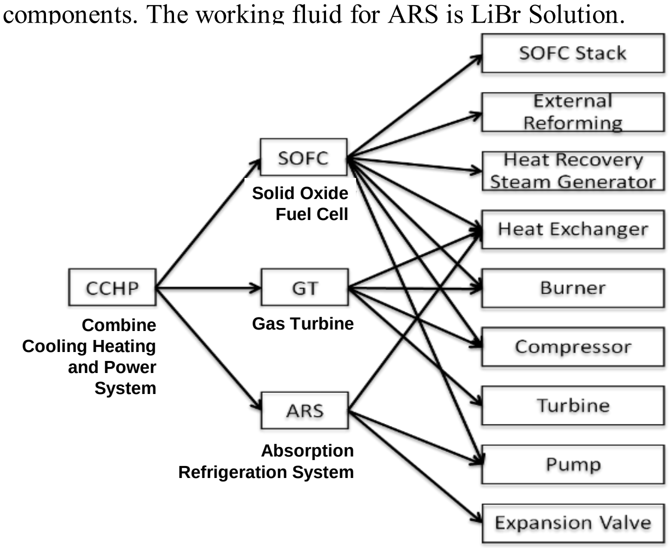


Figure 3. Combined Cooling, Heating, and Power System Flow Chart

1. Mathematical Model

The chemical reactions for SOFC are as follows:

$$\begin{aligned} &\text{Reforming:} && CH_4 + H_2O \rightarrow CO + 3H_2 && \Delta H = 227\,kJ/mol \\ &\text{Shifting:} && CO + H_2O \rightarrow CO_2 + H_2 && \Delta H = -33\,kJ/mol \\ &\text{Electrochemical:} && H_2 + 0.5O_2 \rightarrow H_2O && \Delta H = 241.8\,kJ/mol \end{aligned} \quad (1)$$

The mathematical model of the mole fraction of methane changes with flow position (L) inside the flow channel of SOFC is referred to [1]:

$$CH_4(L) = CH_{4\_in} \exp\left[-\frac{A_s}{h_f} \frac{P_{an}}{n_{an}^{in}} k_0 \exp\left(-\frac{E_a}{\bar{R}T_{SOFC}} \right) L \right] \quad (2)$$

where A_s is the cross-sectional area of the flow channel; h_f is the anode flow channel height; P_{an} is the anode pressure; n_{an}^{i} is the total anode inlet molar flow rate; k_0 is the proportionality constant; Ea is the activation energy (82kJ/mol); $CH_4(L)$ represents the mole fraction of methane changes with flow position. According to Bossel [1], we use the shifting and reforming equilibrium constants to evaluate the components change within the flow channel.

Assuming that the chemical energy into electrical energy reaction inside SOFC is reversible, and according to Nernst equation, the pressure is within the fuel cell operating range. Gibbs free energy can be used to replace reactive gas partial pressure, and the theoretical potential:

$$E_n = \frac{-\Delta G}{n_e F} = E_0 + \frac{RT_{SOFC}}{2F} \ln \frac{P_{H_2} P_{O_2}^{1/2}}{P_{H_2O}} \quad (3)$$

where n_e represents the number of released electrons when reacted. If the fuel within the fuel cell stack is hydrogen, then $n_e = 2$. E_0 represents the potential under standard conditions, and can be obtained by the empirical formula:

$$E_0 = 0.021682[57.939 - T_{SOFC}(11.527 \times 10^{-3} + 0.6 \times 10^{-6} T_{SOFC})] \quad (4)$$

According to the second law of thermodynamics, some of the energy generated by the reaction must be consumed to overcome resistance or obstacle of the reaction. As a result, the output voltage will be lower than the reversible voltage. This is so called polarization, and the phenomenon caused by the total voltage drop is called the over-potential. The polarization over-potential of the SOFC electrochemical reaction can be divided into three parts: (a) activation over-potential, (b) ohm over-potential, and (c) concentration over-potential. The theoretical potential subtracting the over-potential is the actual operating voltage. The efficiency of the heat exchanger (η_{HX}) is defined as the ratio between the actual heat transfer rate and the theoretical maximum heat transfer rate:

$$\eta_{HX} = \frac{Q_{actual}}{Q_{\max}} \quad (5)$$

The heat transfer temperature model is shown in Figure 4. The inlet temperature is known, and the largest ΔT_{max} is the difference between inlet and exit temperatures. Theoretically, the maximum amount of heat transfer is the lesser amount of (1) the heat received by the cold end and (2) discharged by the hot end. It can be expressed into the following formula:

$$Q_{\max} = \min[C_{p_{hot}} m_{hot} \Delta T_{\max}, C_{p_{col}} m_{col} \Delta T_{\max}] \quad (6)$$

where C_p is the isobaric specific heat, m is the mass flow rate; the subscript hot is from the hot end; col is from the cold end. The actual heat transfer rate can be expressed as the Q_{actual}:

$$Q_{actual} = C_{p_{hot}} m_{hot} \Delta T_{hot} = C_{p_{col}} m_{col} \Delta T_{col} \quad (7)$$

where ΔT_{hot} and ΔT_{col} are the actual temperature differences of the cold and hot end respectively.

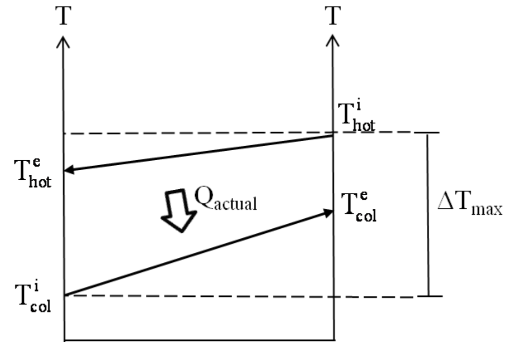


Figure 4. Heat Exchanger Thermal Flow Model

The combustion chamber lies behind the cell stack. Additional fuel can be added into the combustion chamber to increase the combustor exit temperature. The combustion released heat will heat other gases (CO_2, H_2O, N_2, and surplus O_2) as well. When balanced, the temperature will be the combustor final exit temperature. Numerical iterations of energy conservation are used to calculate this temperature.

Assuming the compressor and turbine are isentropic, the ideal gas isentropic relation has, PV^k = constant:

$$w_{isen,C} = \frac{kRT_C^i}{k-1}\left[\left(\frac{P_C^e}{P_C^i}\right)^{\frac{k-1}{k}} - 1\right] \quad (8)$$

$$w_{isen,T} = \frac{kRT_T^i}{k-1}\left[\left(\frac{P_T^e}{P_T^i}\right)^{\frac{k-1}{k}} - 1\right] \quad (9)$$

Compressor efficiency (η_c) is expressed as the ideal power ($w_{isen,C}$) divided by the actual input power (w_{real}). The turbine efficiency (η_T) is expressed as the actual output power (w_{real}), divided by the ideal output power ($w_{isen,T}$), while the actual input and output power can be obtained by the following:

$$w_{real} = h_e - h_i = C_p\left(T_e - T_i\right) \quad (10)$$

The nature of the LiBr solution is referred to Chua et al. [2]. The reference point of the LiBr solution is defined as the weight concentration of 50% and 0℃. Table 1 shows the LiBr solution enthalpy at different concentration and temperature values.

Table 1. Temperature vs LiBr Solution Enthalpy

		Temperature(℃)													
		0	10	20	30	40	50	60	70	80	90	100	110	120	130
X(wt%)	45	-8.22	12.43	34.16	56.57	79.40	102.50	125.85	149.05	172.36	195.79	219.32	242.97	266.73	290.59
	50	-0.02	18.95	39.18	60.31	81.88	103.69	125.76	147.62	169.58	191.65	213.81	236.08	258.45	280.93
	55	17.03	34.30	52.95	72.70	92.97	113.48	134.25	154.75	175.35	196.04	216.82	237.71	258.69	279.78
	60	-	-	77.79	95.97	114.77	133.86	153.20	172.24	191.37	210.58	229.89	249.31	268.83	288.46
	65	-	-	-	-	-	165.01	182.81	200.28	217.84	235.48	253.23	271.09	289.07	307.16

2. System Configurations

In this study, the SOFC/GT system basic assumptions are as follows:

1. methane is used as fuel; oxygen in the air is used as the

oxidant.
2. 10% of the fuel participates in the reforming reaction process.
3. electric current density is constant and independent of the position change of the flow channel.
4. cell stack is operating at average temperature and pressure, neglecting pressure losses.
5. hybrid power system operates at steady state.
6. the fluid is assumed ideal gas.

The SOFC/GT system configuration (Figure 5) and the parameter settings are based on pressurized system. In this configuration, the discharge waste heat is at 500K, and the composition of the discharged gas is basically CO_2, O_2, H_2O, and N_2.

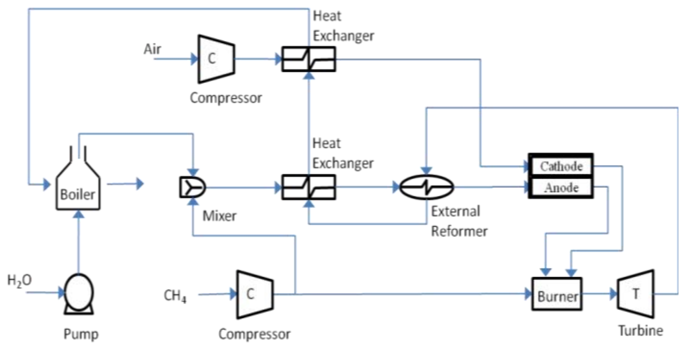


Figure 5. SOFC/GT Pressure System Configuration

Figure 6 is a double-effect LiBr solution absorption refrigeration system. Thermodynamic properties of the working fluid were used in the equation of state. Theoretical analysis and mathematical model were established to simulate the effects of temperature, concentration, and heat exchanger efficiency parameters for the system. To simplify the system analysis, some assumptions are made in this ARS system,

1. temperature is assumed uniform inside the generator, absorber, condenser, and evaporator, respectively.
2. dense solution leaving the generator is at pressure and concentration equilibrium condition; the refrigerant gas leaving the generator is at saturated vapor state.
3. absorbent is not contained in the gaseous refrigerant entering the condenser.
4. refrigerant entering the condenser is at saturated liquid phase and at condensation temperature.
5. refrigerant leaving the condenser is at saturated gas phase and at vaporization temperature.
6. dilute solution leaving the absorber is at pressure and concentration equilibrium conditions.
7. assume the line pressure and heat transfer losses of the pipe to the ambient are negligible.

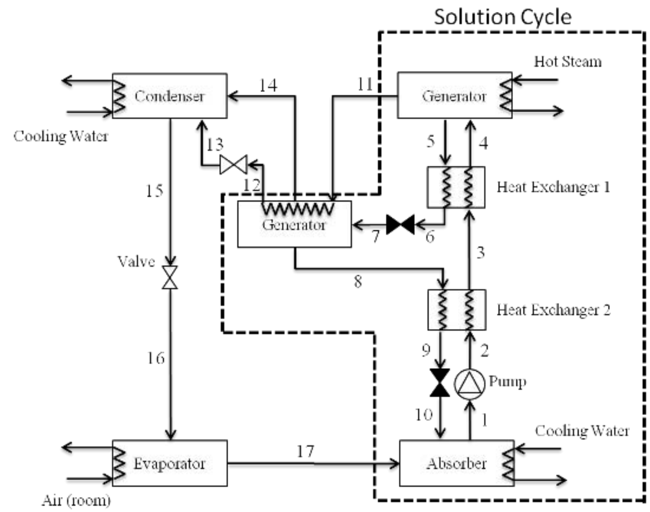


Figure 6. Double Effect Absorption Refrigeration System Diagram

3. System Efficiency

The overall fuel efficiency of CCHP system can be divided into (1) electric efficiency, (2) heating efficiency, and (3) cooling efficiency:

(1) electric efficiency (η_e) is the ratio between total electricity generation (W_{total}) and fuel LHV (Q_{fuel}).
(2) heating efficiency ($\eta_{heating}$) can be defined as the ratio between heat available ($Q_{heating}$) and fuel of low heating value (Q_{fuel}).
(3) cooling efficiency ($\eta_{cooling}$) is the ratio between cooling capacity ($Q_{cooling}$) and fuel LHV (Q_{fuel}).

Fuel efficiency (η_{fuel}) can be defined as the sum of the three:

$$\eta_{Fuel} = \eta_e + \eta_{heating} + \eta_{cooling}$$
$$= \frac{W_{total}}{Q_{Fuel}} + \frac{Q_{Heating}}{Q_{Fuel}} + \frac{Q_{Cooling}}{Q_{Fuel}} = \frac{W_{total} + Q_{Heating} + Q_{Cooling}}{Q_{Fuel}} \tag{11}$$

The SOFC module was verified by our test data. The GT and SOFC/GT modules were compared to a commercial code (GASTURB) and literature data. Both the single- and double-effect ARS modules were verified with available literature results.

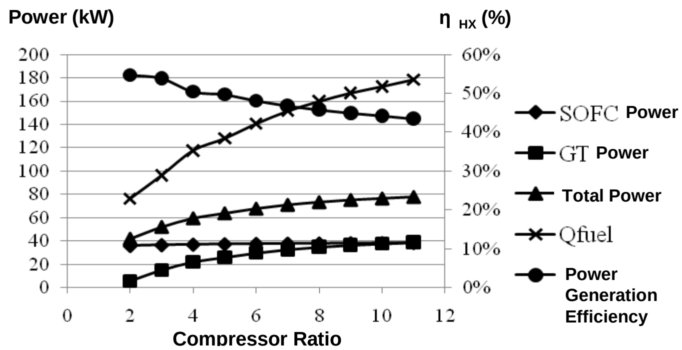
RESULTS AND DISCUSSION

Parametric analysis is first performed. Using the analysis results, an optimized system can be defined. Finally, SOFC, GT and ARS modules are combined to simulate a CCHP system.

1. Parametric Study

Parametric studies were performed using (1) compression ratio, (2) SOFC stack temperature, and (3) ARS concentration parameters.

(1) The compression ratio is defined as the ratio between the compressor outlet pressure and compressor inlet pressure. Figure 7 shows the compression ratio effects on the SOFC, GT, and SOFC/GT combined power and efficiency. By increasing the compression ratio, one can improve the GT efficiency. However, as the cell stack inlet temperature and heat exchange efficiency remain fixed, additional fuel will be needed to add to the combustion chamber to maintain the same heat exchange efficiency. As a result shown in Figure 7, the combined SOFC/GT efficiency decreased as compression ratio increased. Also shown in Figure 8, the total power decreases with increased heat exchanger efficiency. Solid oxide fuel cells are of high temperature fuel cell type. Consequently, the heat exchanger is an indispensable component. As shown in Figure 9, the higher the efficiency of the heat exchanger results in less



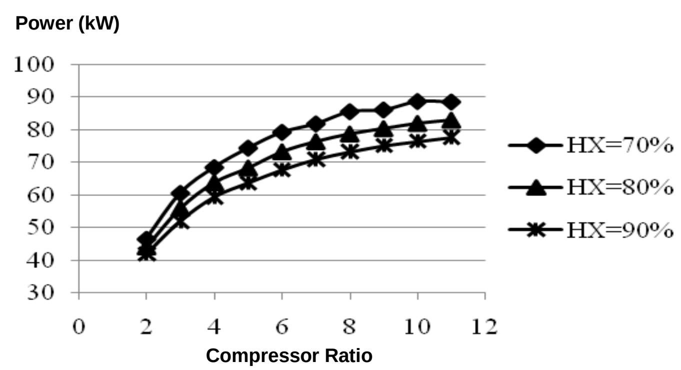


Figure 8. Power vs. Compressor Pressure Ratio at different Heat Exchanger Efficiency

(2) Operating at higher temperatures, the SOFC has the highest efficiency compared to other fuel cells. Figure 10 shows the parametric studies of the SOFC stack temperature effects on the SOFC, GT, and SOFC/GT combined power. The results show that when the temperature of the cell stack is higher than 800℃, the SOFC power is stable, with the GT power increasing linearly with temperature. The overall efficiency effects are shown in Figure 11. As shown in Figure 11, when the temperature is lower than 800℃, both SOFC and SOFC/GT systems are of lower performance. As the temperature is higher than 800℃, it is demonstrated that the

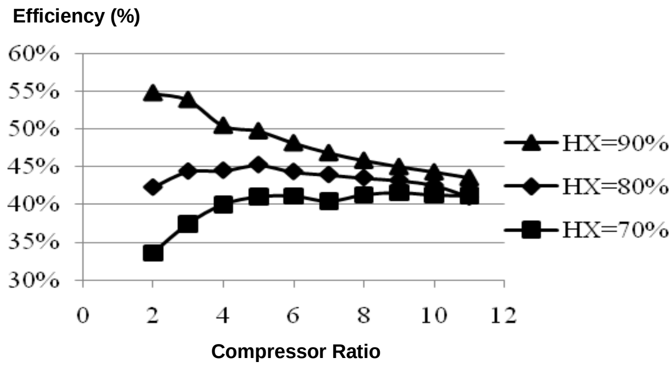
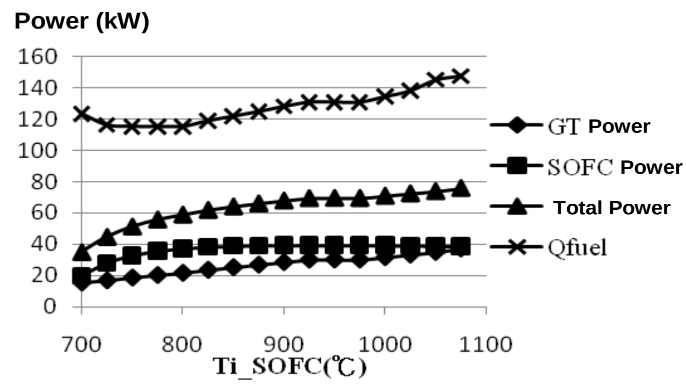


Figure 9. Analysis of the Efficiency of Heat Exchanger



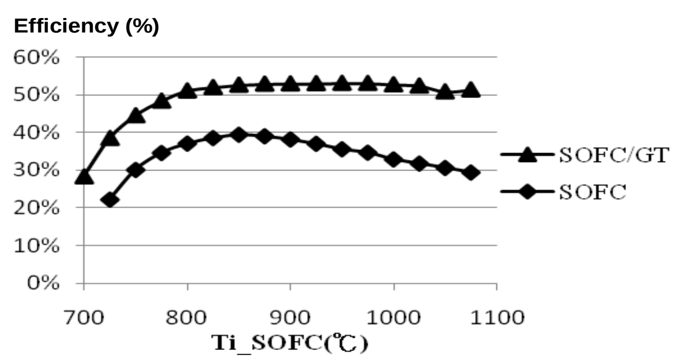


Figure 11. Analysis of the Temperature Parameters on the Efficiency

(3) In the absorption refrigeration system, the higher the generation temperature, the lower the Coefficient of Performance (COP). When simulating under fixed input, the generator temperature increases while the refrigerant flow decreases. As a result, the cooling capacity and performance of coefficient will decrease, as shown in Figure 12.

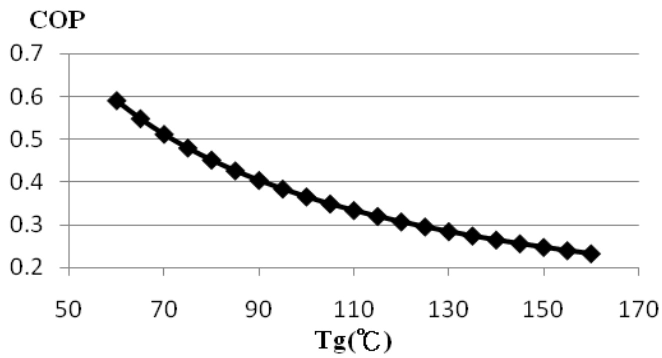


Figure 12. Generator Temperature on the Coefficient of Performance Analysis

The working fluid in the ARS is the LiBr solution. If the concentration difference between the strong solution and the weak solution increases, the more refrigerant is produced, and the coefficient of performance will increase. As demonstrated in Figure 13, if we reduce the weak solution concentration, the coefficient of performance will increase. Similarly, if we increase the strong solution concentration, the COP also increases (Figure 14).

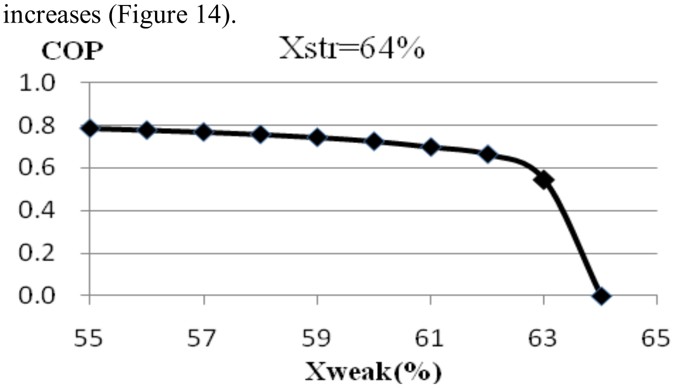


Figure 13. Dilute Solution Concentration on the Analysis of Coefficient of Performance

In the double-effect absorption refrigeration system, there is an intermediate (X_{mid}) concentration solution in addition to the strong and weak solutions. This concentration will affect the solution to the first and second generator refrigerant flow and coefficient of performance. As shown in Figure 15, an increase of the X_{mid} concentration will result in a COP reduction. In addition, the X_{mid} will affect the low temperature generator energy balance, causing the high pressure to change. Figure 16 shows that the X_{mid} increase can cause the system high pressure to increase. Thus, the generator pressure can be adjusted by using the X_{mid} concentration.

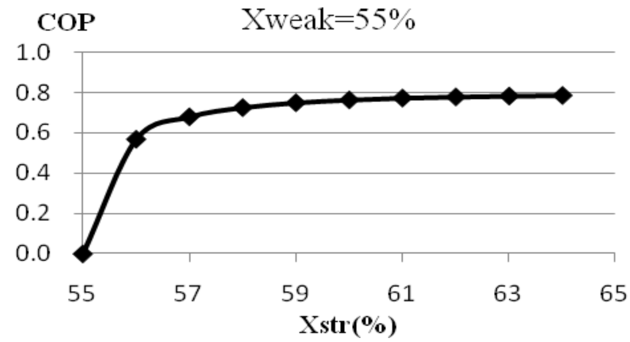


Fig. 14. Strong Concentration on the Coefficient of Performance Analysis

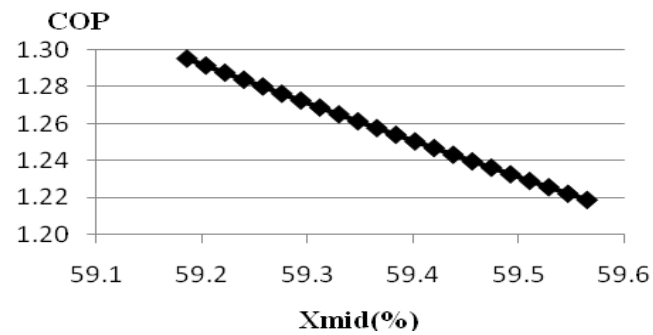


Fig.15. The Concentration of Solution on the Divided Coefficient of Performance

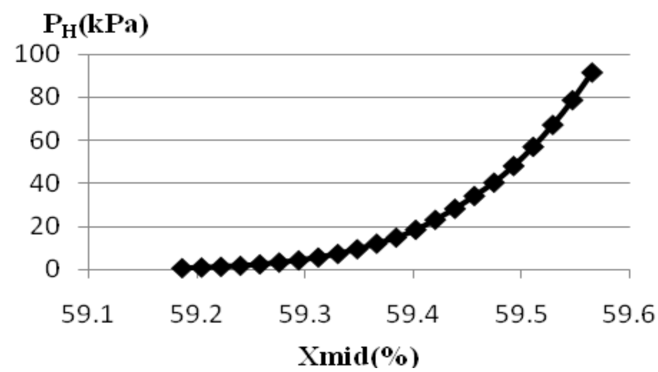


Fig.16. Concentration of Solution on the High Pressure

2. System Optimization

The parametric analysis results of compression ratio, SOFC stack temperature, and ARS concentration parameters were used to perform a parametric optimization simulation. The maximum temperature difference within the cell stack is maintained at 150℃, and the SOFC/GT system optimized result is shown in Figure 17. Total generating capacity includes GT 47kW (38%), SOFC 76kW (62%). Electricity power efficiency is up to 52%, and the overall efficiency of the BOP is 93.7%. Finally, the exhaust heat is 99.35kW at 587.2K, which is used as the heat for ARS.

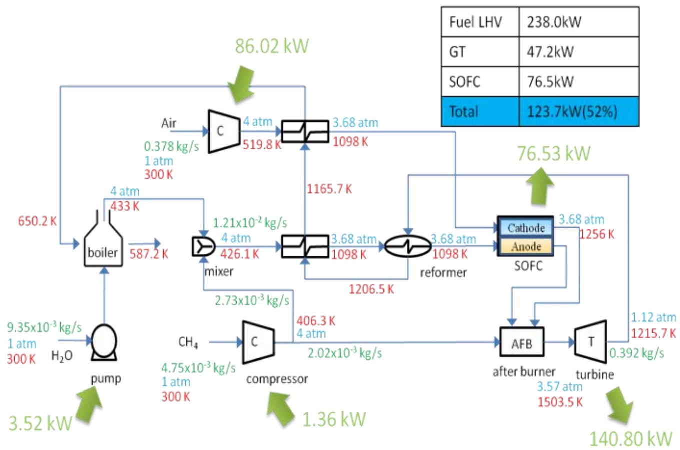


Figure 17. SOFC / GT Optimal Results

Through the ARS temperature and concentration parametric analysis, this study can optimize the ARS simulation parameters. Figure 18 shows the optimized double-effect ARS system. The optimized COP of the double-effect system is 1.34. As compared with the baseline case with a COP of 1.10, the optimized ARS system has demonstrated a 22% increase in COP.

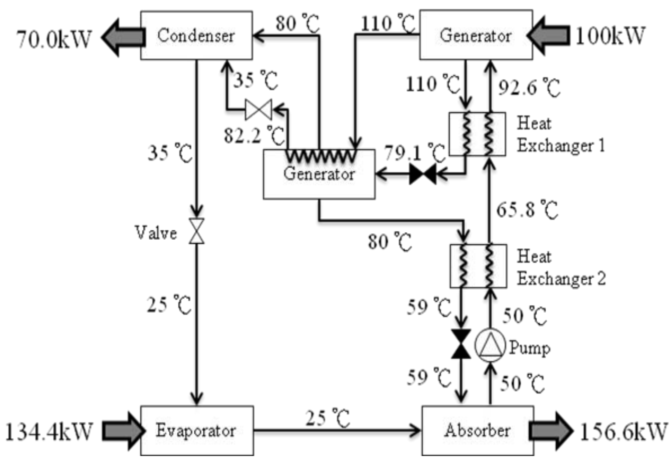


Figure 18. Optimized Double Effect ARS

3. CCHP System

The electricity energy of CCHP is generated by the SOFC/GT combined system. The cooling ratio, R_C, as shown in Equation (12), is defined as the percent of the waste heat which will go to the ARS.

$$R_c = \frac{Q_{avail} \text{ to the ARS}}{Q_{avail}} \qquad (12)$$

If R_C =1, then all the waste heat will be used for cooling. On the other hand, if R_C =0, then all the waste heat will go to heating. Figure 19 shows the electricity efficiency, heating efficiency, and cooling efficiency as functions of R_C. The total fuel efficiency can be more than 100% since COP can be greater than 1, as also observed in literature.

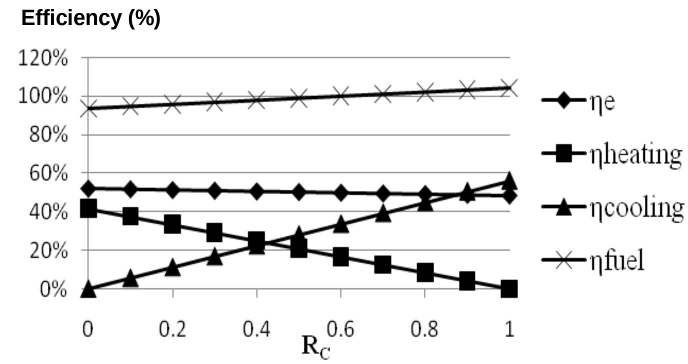


Figure 19. CCHP Simulation Results

As shown in Table 2, a CCHP system example was compared with a regular community residence of 100kW class power consumption. For the CCHP system, if R_C = 1, then an input 100kW of energy can produce 48.3kW of electricity and 56.1kW of cooling capacity, which demonstrated an overall fuel efficiency of 104%.

Table 2. CCHP and Current Energy Supply System Comparison

Power and Cooling	CCHP	General Residential and Commercial systems
Energy of Electricity (kW)	48.3	48.3
Fuel (kW)	100 (48.3%)	134.2 (36%)
Air-conditioning (kW)	56.1	56.1
Fuel (kW)	--	44.5 (0.36×3.5=1.26)
Total fuel (kW)	100	178.7
Overall fuel efficiency (%)	104	58.4
Comment	generate electricity at higher efficiency and free air conditioning from waste heat to ARS	generate electricity at lower efficiency and air conditioning generated by the electric power

As compared to the present situation of energy supply, 134.2kW of fuel need to be burned to produce the 48.3 kW of electricity (using 36% power generation efficiency). The additional cooling of 56.1kW will need another 44.5kW fuel burn (using COP = 3.5). Therefore, the overall fuel efficiency will be 58.4% as compared to the CCHP 104%. It is demonstrated that using the double-effect CCHP system can save up to 44% of energy savings, as shown in Table 2.

CONCLUSIONS

The analysis of SOFC/GT combined with ARS to be applied to a CCHP system was developed in this study. A parametric study as well as an optimized analysis was also performed using this program. The following conclusions were obtained.

Compression ratio can increase the power of the gas turbine. However, additional fuel is needed to be added into the combustion chamber, which maximizes the power output of the system. The maximum power output is shown to be inversely proportional to the heat exchange efficiency. High heat exchange efficiency can reduce the input of fuel, and increase the system efficiency. However, high heat exchange efficiency will reduce the flow and thus decrease the power output. If SOFC stack temperature is below 800℃, the efficiency will be greatly reduced.

It was demonstrated that the SOFC/GT hybrid system can increase the power generation efficiency by 10% - 20%, as compared to the SOFC system alone. Also, ARS system prefers lower generator temperature, greater concentration difference, and lower intermediate concentration.

Finally, using the CCHP system as an example to compare with the current centralized utility system, the fuel utilization of the CCHP system with a double-effect ARS combined with SOFC/GT is 104%. As compared with the existing utility power system of only 58.4% fuel efficiency, a 44% of energy savings are realized.

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