แบบจำลองเทอร์โมไดนามิกส์เชิงตัวเลขของระบบผลิตกำลังงานไฟฟ้าผสมระหว่างเซลล์เชื้อเพลิงชนิดออกไซด์แข็งและกังหันก๊าซ

Numerical Thermodynamics Models of the Solid Oxide Fuel Cell (SOFC) and Gas Turbine (GT) Hybrid Systems

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บทคัดย่อ

งานวิจัยนี้ได้ทำการสร้างแบบจำลองทางเทอร์โมไดนามิกส์ของระบบผลิตกำลังงานไฟฟ้าผสมระหว่างเซลล์เชื้อเพลิงชนิดออกไซด์แข็ง (SOFC) และกังหันก๊าซโดยใช้โปรแกรม MATLAB ในเบื้องต้นนี้โครงสร้างของระบบผลิตกำลังงานไฟฟ้าผสมได้ถูกพัฒนาและวิเคราะห์ขึ้นมาด้วยกันสองโครงสร้าง ทำการศึกษาเปรียบเทียบพารามิเตอร์ที่แสดงถึงสมรรถนะของระบบ เช่น กำลังการผลิตไฟฟ้าของเซลล์เชื้อเพลิงชนิดออกไซด์แข็ง, อุณหภูมิของก๊าซที่เข้าสู่กังหันก๊าซ หรืออุณหภูมิของไอเสียที่ออกจากระบบ เพื่อให้สามารถเลือกโครงสร้างของระบบผลิตกำลังงานไฟฟ้าผสมที่ดีที่สุดได้ ซึ่งในกระบวนการเลือกโครงสร้างของระบบผลิตกำลังงานไฟฟ้าที่ดีที่สุดสำหรับกังหันก๊าซและเครื่องอัดอากาศคำนวณโดยใช้สมการทางเทอร์โมไดนามิกส์ และได้ทำการตรวจสอบความถูกต้องของแบบจำลองโดยได้นำผลการคำนวณไปเปรียบเทียบกับผลการคำนวณจากงานวิจัยก่อนหน้า

คำสำคัญ: กังหันก๊าซ แบบจำลอง ประสิทธิภาพ เซลล์เชื้อเพลิงชนิดออกไซด์แข็ง ระบบผลิตกำลังงานไฟฟ้าผสม

Abstract

In this work, a detailed thermodynamic model of a SOFC/Gas turbine hybrid system is simulated in MATLAB. A few configurations of the hybrid systems are proposed and analyzed. A comparative study based upon performance parameters, such as SOFC power, turbine inlet temperature, and exhaust temperature was used to select the best configuration. Simple thermodynamic models for the compressor and turbine are used during the configuration selection. The results are compared to the available literature.

Keywords : Efficiency, Gas Turbine, Hybrid, Model, Solid Oxide Fuel Cell

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Introduction

To overcome the threats posed by climate change and energy security, advanced clean energy technologies are urgently needed. Hybrid fuel cell systems have emerged as attractive power generation solutions with great promise for high energy/power efficiency with reduced environmental emissions, allowing the shift from a fossil fuel-based economy to a new paradigm in a progressive manner. Amongst the various types of fuel cell hybrids, the combination of solid oxide fuel cell (SOFC) and gas turbine (GT) has been identified as a key technology superior to many other options due to its fuel flexibility and ultra-high energy conversion efficiency[1,3]. It has been demonstrated by simulation technique that SOFC can achieve 50% net electrical efficiencies and have already been considered feasible for integration with multi-MW gas turbine engines to achieve considerably high electrical efficiency[4]. Siemens-Westinghouse Power Corporation developed the first advanced power system, which integrates a SOFC stack with the gas turbine engines. The pressurized (3 atm) system generates 220 kW of electrical power at a net electrical efficiency of 55%[5]. In spite of the advantages of the SOFC-GT hybrid system, many technical barriers have to be overcome for the successful commercial development of this power generation technology. Therefore, design parameters need to be varied to determine performance sensitivity, and fundamental analysis is still needed to determine the practical operating conditions for most efficient operation. System modeling combined with thermodynamic optimization can be a valuable tool in technological research, providing indications of technical feasibility, identifying ways to improve efficiency, and determining the better configuration and conditions for an integrated power plant. To make a thorough investigation of the optimal integration amongst a fuel cell, gas turbine and other system components, the thermodynamic modeling is developed in the present study to systematically optimize the SOFC-GT hybrid cycle based upon previous system modeling work[6]. This methodology is based on SOFC-GT hybrid cycle model with an optimization algorithm developed using MATLAB to efficiently explore the range of possible operating conditions and will extend the code developed previously for possible part load simulation in the future.

SOFC – gas turbine hybrid system models

A gas turbine cycle is based on the Brayton cycle, which is a simple series of compression, combustion, and expansion processes. The main components of the cycle are a compressor, a combustor, and a gas turbine. The number of components is not limited to three as the cycle may consist of several compressors and turbines.

Gas turbine engines are generally used for power production falling in the range of few kilowatts to several megawatts and offer an electrical efficiency of 30-40%. This can be further improved by adding a topping cycle to achieve efficiencies of up to 60%. A gas turbine can be *directly or indirectly connected to the SOFC*. In an indirect integration, the combustor of the gas turbine is replaced with a heat exchanger in which air from the compressor is heated by the fuel cell exhaust and the SOFC can operate under atmospheric conditions. Although, it reduces the sealant requirement in the SOFC stack, the heat exchanger has to operate at very high temperatures and pressure differences. The material requirements in the indirect integration are really an issue and hence, it is not generally used. Figure 1 shows a direct integration of a solid oxide fuel cell and a gas turbine system. As can be seen from it, the combustion chamber of the gas turbine engine has been replaced with an SOFC and an afterburner. The pressurized stream from the compressor goes into the SOFC. The exhaust from the SOFC goes to the afterburner and the resulting high temperature and pressure exhaust enters into the turbine. In this case, the SOFC operates at high pressure, which further improves its performance. Moreover, heat exchangers are added after the turbine exhaust to further utilize the waste heat in preheating of the streams entering the SOFC stack. The high-pressure operation of SOFC stack causes large pressure gradients between anode and cathode. This pressure imbalance needs to be avoided, due the brittleness of the SOFC materials, and good sealants are required to stop leakages[1, 7].

Selecting a configuration is one of the key steps before designing a hybrid system. This topic presents few configurations of the SOFC - gas turbine hybrid system and discusses why one configuration is better than the other. Once the better configuration is selected, a complete cycle analysis is presented. The modeling equations are shown below.

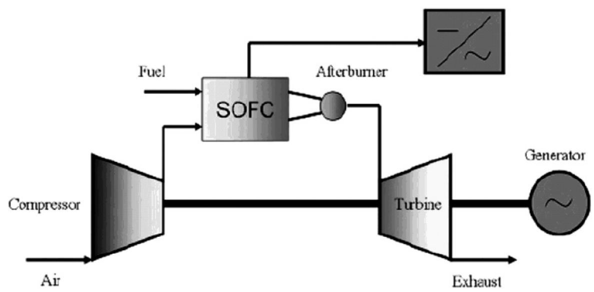

Figure 1 Gas turbine engine as a bottoming cycle in a SOFC-gas turbine System[7]

Solid oxide fuel cell modeling

A SOFC stack has been modeled using MATLAB[8]. Other components of the hybrid system like heat exchanger, compressor, gas turbine, and combustor have been modeled using the same simulation tool. All the components have been integrated to form a cogeneration power system and thermodynamic behavior the cycle is being studied.

Component models

Compressor model:

In the hybrid system, ambient air is compressed using the compressor and supplied to the SOFC. Model of the compressor is based on the perfect gas equations and polytropic transformations. Following equations have been used in compressor model:

The exhaust temperature:

$$T_e = T_i \left(p_e/p_i\right)^{\left(\left(\gamma_a-1\right)/\gamma_a\eta_{\infty c}\right)} \qquad (1)$$

Where, i-inlet, e-exit, P-pressure, T-temperature, $\gamma_a = C_{pa}/C_{va}$ -ratio of specific heats of air, $\eta_{\infty c}$ - polytropic efficiency of the compressor.

Change in isentropic enthalpy:

$$\Delta h_c = C_{pa} T_i \left(P_e/P_i\right)^{R_a/C_{pa}} - 1 \qquad (2)$$

Efficiency of the compressor:

$$\eta_C = \left(1-(p_e/p_i)^{\left(\frac{\gamma_a-1}{\gamma_a}\right)} \bigg/ 1-(p_e/p_i)^{\left(\frac{\gamma_a-1}{\gamma_a\eta_{\infty C}}\right)} \right) \qquad (3)$$

Mechanical power consumed by the compressor:

$$P_C = \left(q_{air}\Delta h_C\right)/\left(\eta_C\eta_{trans}\right) \qquad (4)$$

Where q_{air} is the air flow rate in kg/s and η_{trans} is the transmission efficiency from turbine to compressor.

Turbine model:

In the hybrid system, a turbine is used to drive the compressor and as a secondary electrical power device. The turbine has been modeled in the same way as the compressor

The exhaust temperature:

$$T_e = T_i \left(p_e/p_i\right)^{(\gamma_g-1)/\gamma_g\eta_{\infty TG}} \qquad (5)$$

Where, $\gamma_g = c_p / c_v$ - ratio of specific heats of combustion gases, $\eta_{\infty TG}$ -polytropic efficiency of the turbine.

Change in isentropic enthalpy:

$$\Delta h_{TG} = C_{pg} T_i \left(p_e/p_i\right)^{R_g/C_{pg}} - 1 \qquad (6)$$

Gas turbine efficiency:

$$\eta_{TG} = \left(1-(p_e/p_i)^{\left(\frac{\gamma_a-1}{\gamma_a\eta_{\infty TG}}\right)} \right) \bigg/ \left(1-(p_e/p_i)^{\left(\frac{\gamma_g-1}{\gamma_g}\right)} \right) \qquad (7)$$

Now, the mechanical power delivered by the gas turbines can be calculated as:

$$P_{TG} = \eta_{TG} q_{TG} \Delta h_{TG} \tag{8}$$

And finally, mechanical power delivered to the Generators to produce electricity:

$$P_{MG} = P_{TG} - P_C \tag{9}$$

Heat exchanger model:

A hybrid system is a parallel flow heat exchanger model. Following is the concept used to model the heat exchanger:

Where, C_h-heat capacity of the hot stream, C_c-heat capacity of the cold stream, U-Overall heat transfer coefficient, A-Total heat transfer area And, DT_1 and DT_2 are the stream-to-stream temperature differences in the front and back section of heat exchanger:

$$\Delta T_1 = T_{h,1} - T_{c,1} \tag{10}$$

$$\Delta T_2 = T_{h,2} - T_{c,2} \tag{11}$$

The proportionality between total heat transfer rate q and the overall thermal conductance of the heat exchanger surface is:

$$q = UA\Delta T_{lm} \tag{12}$$

Where DT_{lm} is the log mean temperature difference (LMTD) and defined as under:

$$\Delta T_{lm} = \left(\Delta T_2 - \Delta T_1\right) \Big/ \left(\ln\left(\Delta T_2 / \Delta T_1\right)\right) \tag{13}$$

and, $dq = -CdT$ gives the streams exit temperatures once q is known.

Combustor Model:

The streams coming out of the fuel cell are combusted with additional fuel and air in the combustor and the high temperature exhaust is sent to turbine. Following equation models the flow in the combustor:

Enthalpy of Fuel Cell Streams + Enthalpy of additional fuel = Net Enthalpy of the mixture

$$dH = C_p (T)\, dT \tag{14}$$

Using above equation and known mixture enthalpy,

$$\Delta h_C = C_{pa} T_i \left(p_e / p_i\right)^{R/C_{pa}} - 1 \tag{15}$$

Exhaust temperature is calculated. As of now, model assumes the complete combustion and there are no NO_x formed during the combustion.

Model assumptions

Hydrogen is used as fuel that the composition by mol is 97% H_2 and 3% H_2O. Air composition by mol is 21% O_2 and 79% N_2. The fuel pump power is not included while calculating the cycle efficiency. Pressures losses in the fuel cell, combustor, and piping are negligible. The combustor of the model is based on simple combustion reactions and the complete system is adiabatic. The operating conditions for the cycle components are the compressor pressure ratio and turbine pressure ratio is 2.9. Design temperature and pressure is 25 °C and 1 atm. For SOFC that is a current density equal to 1.00 A/cm^2 and cell voltage equal to 0.8 volt. It was selected from a polarization curve that was produced in MATLAB.

Cycles analysis

In this work, a few configurations of the hybrid system are simulated and their performances are analyzed. Based upon the comparative study, the better configuration is chosen and discussed in detail. The basic parameters that are focused on, in choosing the optimum configuration, are the cycle efficiency and the fuel cell power. Initial numbers like SOFC power required, heat exchanger, turbine or compressor specifications etc. are temporary numbers and have been assumed to get an idea how system performance depends upon the operating parameters. These numbers can be changed depending upon the system requirements. The first configuration has been chosen based upon the idea that since combustor exhaust is at high temperature, even the low mass flow rate will be enough to heat the fuel stream to a required temperature. The second configuration is the proposed configuration and the only difference is that here both (fuel and air) the streams are heated by the turbine exhaust. Both configurations are shown below in figures 2 and 3. For both configurations the compressor, SOFC, turbine and combustor efficiencies are 68.5%, 45%, 88.4% and 100 %, respectively.

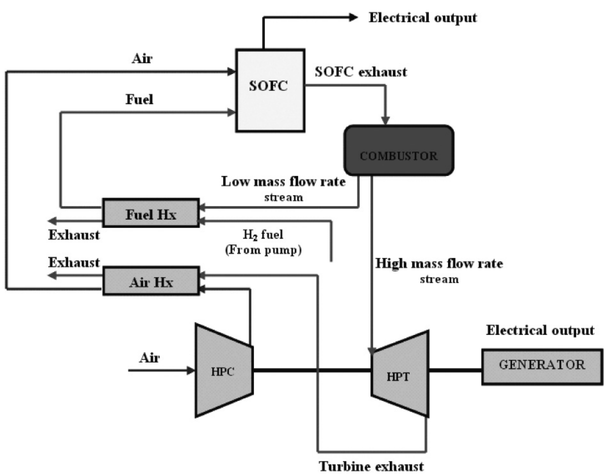

Figure 2 Schematic of the first configuration

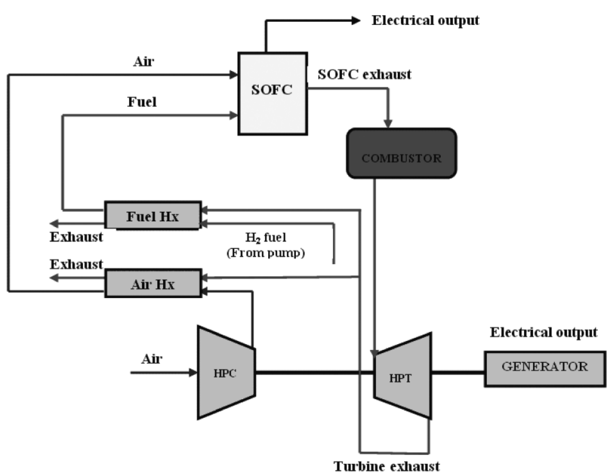

Figure 3 Schematic of the second configuration

From table 1, it can be seen that configuration 2 has lower steady state performance and configuration 1 gives the better.

Table 1 Comparative results for two configurations

	Config. 1	Config. 2
Fuel flow (g/s)	9.62	9.62
Air flow (g/s)	400	400
SOFC temp (°C)	944	832
Turbine Inlet temp (°C)	1136	1166
SOFC power (kW)	359	319
HPT (kW)	104	108
Total power (kW)	463	427
Cycle efficiency (%)	58	53.5
Exhaust temp (°C) (Air HE)	617	605

Configuration 1 gives 58% cycle efficiency. We can say that the low performance of configuration 2 can be attributed to the low operating temperature of the fuel cell stack, as the SOFC performance is directly proportional to the operating temperature. As we instead select from configuration 2 by 1, the operating temperature improves and hence the performance of the fuel cells. Configuration 1 is chosen as the better configuration out of the configurations studied. Due to the compressed high temperature exhaust from the combustor expanding in the turbine a low mass flow rate stream is used to heat the fuel before entering to the SOFC, so it is the reason that the SOFC operating temperature is higher than other configurations. The enthalpy of the exhaust leaving the turbine is high enough to give the required preheating to the air stream in the air heat exchanger. The exhaust from the air heat exchanger is released to the ambient. The cycle efficiency obtained in this case is 58% and the power of the fuel cell is around 77.54% of the total power. The turbine inlet temperature is also within the limits (lower than 1477 °C). For further analyzed in is very interesting to study about the performance and characteristics behavior of the configuration 1 when both of the overall heat transfer coefficient and air mass flow rate are changed for supporting that the configuration 1 is the better configuration and to increase the understanding relationships between the mass flow rate and the overall heat transfer coefficient input variables and the stack temperature (e.g. relate with the power of the fuel cell), the cycle efficiency, the turbine inlet temperature, output variables of the configuration 1 that are shown in figures 4 to 6. Figure 4 is the sensitivity study of the different air flow rates on the variation of the stack temperature for varying of the overall heat transfer coefficient or UA. The stack temperature plot shows that at all of UA, the stack temperature becomes more sensitive to the change of air flow rate. Figure 5 is the sensitivity study of the different air flow rates on the variation of the cycle efficiency for varying of overall heat transfer coefficient or UA. The efficiency plot shows that at UA=7000 $W.K^{-1}$, the cycle efficiency becomes insensitive to the change of air flow rate. When the air flow changes from 0.65 to 0.75, efficiency changes from 65 % to 60% but the stack temperature and turbine inlet temperature improve significantly. Figure 6 is the sensitivity study of the different air flow rates on the variation of the turbine inlet temperature for varying of overall heat transfer coefficient or UA. The turbine inlet temperature plot shows that at all of UA, the turbine inlet temperature becomes more sensitive to the change of air flow rate.

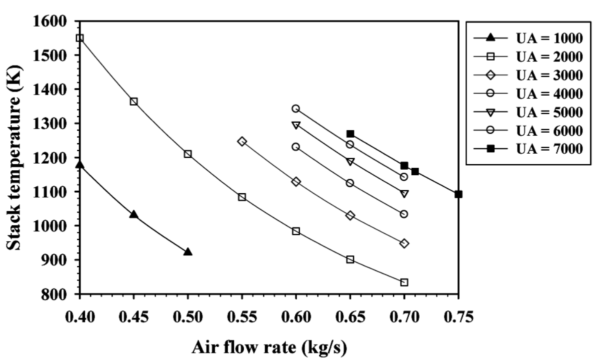

Figure 4 Configuration 1 sensitivity studies of different air flow rates (kg/s) on the stack temperature (K)

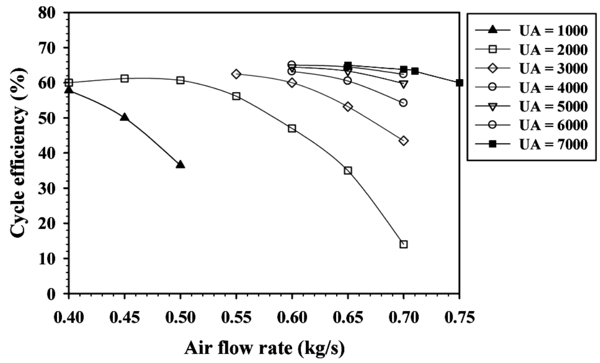

Figure 5 Configuration 1 sensitivity studies of different air flow rates (kg/s) on the cycle efficiency (%)

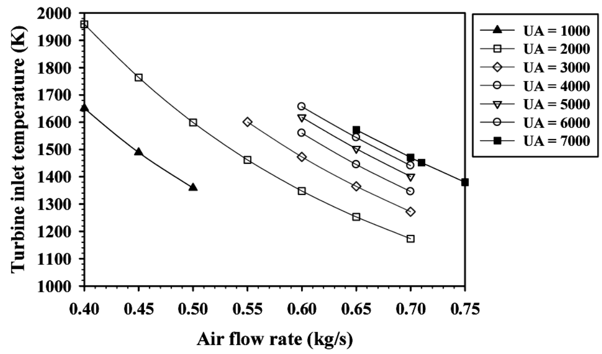

Figure 6 Configuration 1 sensitivity studies of different air flow rates (kg/s) on the turbine inlet temperature (K)

The presented work is an attempt to model the SOFC-GT hybrid system for auxiliary aerospace. The system is designed to produce 440 kW of net electrical power, sized for a typical long-range 300-passenger civil airplane especially at sea level conditions. The system is compared to an earlier version that was designed by Freeh et al.[9] for sea level operation of the aircraft to also produce 440 kW of net electrical power. Freeh et al. designed only one model that has a different schematic arrangement then this present model by including steam generator and fuel reformer, which can use both natural gas and hydrogen that shows in figure 7.

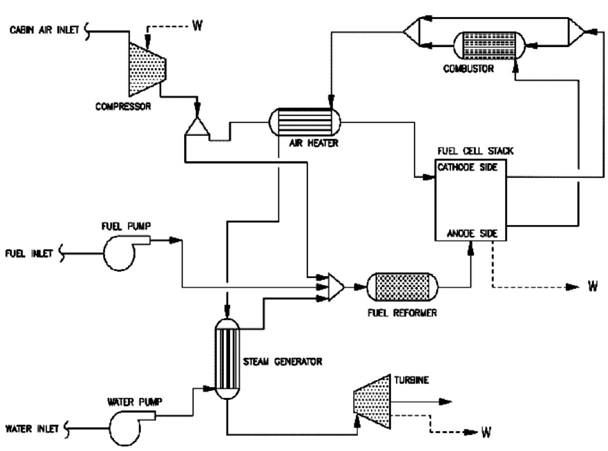

Figure 7 ASPEN model of SOFC-GT hybrid system by NASA Glenn Research Center[9]

Table 2 shows the parameters at the same value as the earlier version of a hybrid system model in order to compare the performance with an earlier version at sea level condition[9]. From table 3 the model is giving better sea level performance than the earlier version[9]. The efficiency observed for the model is 45.1% and the efficiency for the earlier model is 42%. The SOFC power is 71.1% of the total power while this percentage is 95.75 % in the earlier model. The power difference is due to the differentce in the schematic of the components arrangement between two models.

Table 2 The calculation parameters for comparison of the model and an earlier model[9]

	Parameters used	
	Configuration 1	**Earlier hybrid model[9]**
Stack pressure	2.9 bar	2.9 bar
Stack temperature	850 °C	850 °C
Compressor inlet pressure	14.7 psia	14.7 psia
Compressor pressure ratio	2.88	2.88
Compressor efficiency	83%	83%
Turbine outlet pressure	17.1 psia	17.1 psia
Turbine pressure ratio	2.37	2.37
Turbine efficiency	84%	84%

Table 3 Design performance of the model and an earlier model[9]

	Performance results	
	Configuration 1	**Earlier hybrid model[9]**
SOFC net power	342 kW	429 kW
Turbine power	139 kW	19 kW
Total power	481 kW	448 kW
Cycle efficiency	45.1%	42 %

Conclusion

A hybrid solid oxide fuel cell and gas turbine power system models was developed and implemented in MATLAB. Two types of model have been developed based on simple thermodynamic expressions. Some important observations are made during the configuration study. The fuel cell performance is found to be a strong function of operating temperature (which depends upon the preheating of the input streams) and hence when the heat exchanger properties are varied with the air mass flow rate, the cycle performance shifts towards favorable conditions. The parameters that limit the cycle performance are the SOFC temperature, the turbine inlet temperature, and the exhaust temperature. Though at high SOFC temperatures, the cycle efficiency is high, the cycle operation under these conditions is not feasible after a certain point. The results of the presented model (configuration 1) were validated by comparing with the earlier model from available literature.

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