

Thermodynamic Analysis of Gas Turbine – Solid Oxide Fuel Cell (GT-SOFC) Aircraft Auxiliary Power Unit (APU)

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Abstract—In this paper, Gas Turbine – Solid Oxide Fuel Cell (GT-SOFC) Aircraft Auxiliary Power Unit (APU) configuration is thermodynamically investigated. The system has a single stage centrifuge compressor, a heat exchanger, a jet fuel reformer, a SOFC, a combustion chamber and a turbine. The onboard kerosene fuel is converted to H₂ and CO in the jet fuel reformer and used in the SOFC. Excess gases from the SOFC and additional kerosene from the fuel tank are burned in the combustion chamber. The system efficiency is increased significantly decreasing the overall fuel consumption. Although the system total weight increases with the additional elements such as SOFC, heat exchanger and jet fuel reformer, H₂O produced in the SOFC can be used as potable water in the aircraft decreasing the water supply need and balancing the take-off weight of the aircraft.

Index Terms— Aircraft Auxiliary Power Unit (APU), GT-SOFC, Hybrid Power Units, Thermodynamic Analysis.

I. INTRODUCTION

Effect of aviation to anthropogenic CO₂ emission is 2.5% [1]. Demand for air traffic is rapidly growing. According to Boeing Market Outlook World GDP will grow 3.1%, commercial aircraft fleet will grow 3.6% and air traffic will grow 4.9% yearly between 2014 and 2034 [2]. According to Airbus Global Market Forecast, yearly air traffic growth will be 4.5% between 2015 and 2035 [3]. Both Airbus and Boeing which are the biggest aircraft suppliers in the world, forecast 4-5% yearly growth in air traffic between 2015 and 2035. This indicator forces industries and research organizations to investigate more economical and environmental systems and operations so as to minimize operation costs and environmental effects of air travel.

Aircraft's main engines provide the power needed for thrust and systems consumption. There are 3 types of power sources for aircraft systems; electrical, hydraulic and pneumatic as seen in Table I. Electrical systems are more efficient and have lower weight than other power sources. Therefore, aircraft manufacturers are recently directed to More Electric Aircraft (MEA) approach. There would be All Electric Aircraft (AEA) approaches even in the long term strategies so as to minimize environmental effect of aircrafts. By shifting conventional systems power sources from hydraulic and pneumatic to electrical devices there would be significant weight advantages which will further decrease the fuel used. Electrical systems are more advantageous in term of reliability and maintenance costs too.

Boeing 787 is one of the best examples of moving towards MEA approach. Boeing 787 introduced no-bleed system to increase the efficiency and reduce fuel consumption. The predicted operational fuel efficiency is 3% with no-bleed architecture. On Boeing 787, the bleed air is used in cowl de-icing system only, while wing de-icing system, engine start system, hydraulic pump drives and cabin environmental control system are electrified. The new electrical architecture decreased the system weight, reduced part numbers, increased reliability and improved performance of the aircraft. Since the bleed air need is decreased, a simpler APU architecture producing electric power only is mounted on the aircraft [5].

TABLE I
AIRCRAFT POWER SOURCES [4]

Power Source	Conventional System	New Approach - MEA
Electrical	Cabin Lighting, Avionics, Fuel Pumps, etc.	Cabin Lighting, Avionics, Fuel Pumps, Brakes, Flight Controls, Engine start, De-icing, ECS & Pressurization, etc.
	Brakes, Flight Controls, Landing Gear, etc.	Flight Controls, Landing Gear, etc.
Hydraulic	Engine start, De-icing, ECS & Pressurization	Cowl De-icing

APUs; typically provides bleed air for main engine start, air condition system and de-icing system as well as electrical energy which is necessary for the aircraft systems such as back-up purposes during flight or on the ground. Auxiliary Power Units (APU) that are used for commercial aircrafts are gas turbine engines. They generally have a single stage centrifuge compressor, a combustion chamber, a single stage turbine and other accessories. Their thermal efficiencies are as low as 15% [6]. Although they use less fuel than main aircraft engines their environmental effects are significant as seen in table II [7].

TABLE II
COMPARISON OF FUEL CONSUMPTION AND EMISSIONS FOR JT8D-219 AND HONEYWELL GTCP 131 [7]

	Power Rate	Fuel Consumption (kg/s)	HC mg/m ³	NO _x Mg NO ₂ /m ³
JT8D-219 (Main Eng.)	Idle	0.13	2.1	3.8
	Max.	1.4	3.6	32
Honeywell GTCP 131 (APU)	Normal	0.013	7.2	48

The Honeywell 131-9A gas turbine APU has 440 kW shaft power and 90 kW electric generator. The APU weight is 163,7 kg and consumes 120 kg fuel per hour [8, 9]. This type of APU is generally used in narrow body aircrafts. Narrow body aircrafts represent %65 of commercial aircraft fleet in 2014 and will represent %70 of commercial aircraft fleet in 2034 [2].

There are two different fuel cell application strategies in aircrafts. First strategy is storing hydrogen onboard aircraft and then using it in low temperature, high power density fuel cells. PEM fuel cells can be used for this strategy. In this case; hydrogen storage equipment must be installed on the aircraft and hydrogen refueling stations must be established at the airports. Second strategy is coupling high temperature fuel cells with gas turbine engines, reforming onboard kerosene to H₂ and using it in fuel cell. SOFC fuel cells can be used for this strategy. This strategy would be eliminating hydrogen storage equipment in aircraft and hydrogen refueling stations at the airports. High temperature fuel cells are heavier than low temperature fuel cells. Therefore, weight estimations should carefully be performed for both strategies. Table III shows the weight effect of fuel cell utilization strategies.

TABLE III
HIGH TEMPERATURE AND LOW TEMPERATURE FUEL CELL WEIGHT EFFECT

	Low Temperature Fuel Cell	High Temperature Fuel Cell
Fuel Cell Weight Increase	Low	High
Jet Fuel Reformer	Not needed	Needed
Heat Exchanger	Not needed	Needed
H ₂ Storage Unit	Needed	Not needed

APU power densities are around 2,5 – 3 kW/kg. Therefore, proposed system should have high power densities so as to be competitive. Solid Oxide Fuel Cells have higher efficiencies than Gas Turbine Engines and they can be easily coupled with Brayton Cycle in which gas turbine engines operate. State of the art of SOFC power density is around 300 W/kg while NASA develops 700 W/kg high power density SOFC stacks [10].

Fuel Cells consume less fuel and produce water during operation. This water can be used as potable water in the aircraft. Potable water in the aircraft is used in galleys and toilets and then stored in waste system. Airbus A320 has 200 liters water tank, which is pressurized with bleed air during

flight. The system uses service panel pressure ports, when the aircraft is on the ground, [11].

II. METHODOLOGY

A. Assumptions

The system schematic is shown in figure 1. The system is assumed to work in steady state conditions. Compressor inlet parameters are chosen as their values at sea level conditions. All the thermodynamic performances of the hybrid system were calculated by a code developed in the MATLAB software.

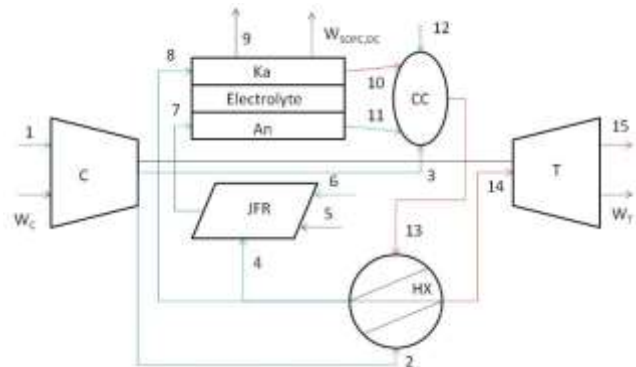


Fig. 1. GT-SOFC Hybrid Auxiliary Power Unit (APU).

The compressor pressure ratio is set between 2 and 4 while the efficiency is assumed to be %80. The turbine efficiency is assumed to be 85%. Turbine inlet temperature is set to 1400 K. Pressure drop in the system is neglected. Honeywell 131-9A gas turbine APU's weight of 163,7 kg is used for weight evaluation.

The heat exchanger effectiveness is taken as 85% while exhaust air temperature is assumed to vary between 700 and 900 K. Accumetrics Cooperation has developed a heat exchanger of 9,61 kg with an effectivity of 85%, airflow and temperature requirements of which are compatible with the operating conditions of the hybrid system studied in this paper [12].

The jet fuel reformer uses water vapor, air and kerosene to produce H₂ and CO. Calculated reformer efficiency is 78,8%. Currently used jet fuel reformers are small scale prototypes. Weight estimation used in this paper was taken from Tornabene et al's predictions as 59,5 kg [13].

It is assumed that a SOFC stack replaces the APU's 90 kW electric generator. The necessary SOFC stack weight was calculated as 128,57 kg, assuming a 700 W/kg power density. Additional systems' weight such as piping and sealing are neglected. 20% of the compressor air directed to SOFC through heat exchanger. A summary of assumptions made for components are given in Table IV.

TABLE IV
COMPONENT PARAMETERS

Component	Parameter
Compressor Efficiency	80%
Compressor Pressure Ratio	2-4
Combustor Efficiency	95%
Turbine Efficiency	85%
Turbine Inlet Temperature	1400 K
Turbine Expansion Ratio	6
Heat Exchanger Effectiveness	85%
SOFC Stack Area	150 cm ²
SOFC Fuel Utilization Ratio	85%
SOFC Air / System Total Air Ratio	0.2

B. Calculations

Mathematical model and chemical reactions used in gas turbine components (compressor, turbine and combustion chamber) performance evaluations are given in equations 1 to 9.

$$\frac{T_{2,iz}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma_{air}-1}{\gamma_{air}}} = \pi^{\frac{\gamma_{air}-1}{\gamma_{air}}} \tag{1}$$

$$\eta_C = \frac{W_{C,iz}}{W_C} = \frac{h_{2,iz} - h_1}{h_2 - h_1} \tag{2}$$

$$W_C = m_{air}(h_2 - h_1) \tag{3}$$

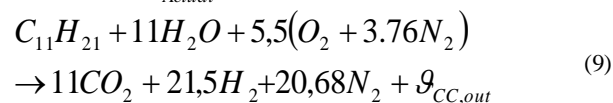
$$\frac{T_{14}}{T_{15,iz}} = \left(\frac{P_{14}}{P_{15}}\right)^{\frac{\gamma_{gas}-1}{\gamma_{gas}}} = \pi^{\frac{\gamma_{gas}-1}{\gamma_{gas}}} \tag{4}$$

$$\eta_T = \frac{W_T}{W_{T,iz}} = \frac{h_{15} - h_{14}}{h_{15,iz} - h_{14}} \tag{5}$$

$$W_T = m_{gas}(h_{15} - h_{14}) \tag{6}$$

$$FAR_{Theoretical} = \frac{m_{Fuel_2}}{m_{air_3}} = \frac{n_{Fuel_2}}{n_{air_3}} \frac{MW_{Fuel_2}}{MW_{air_3}} = \lambda \frac{MW_{Fuel_2}}{MW_{air_3}} \tag{7}$$

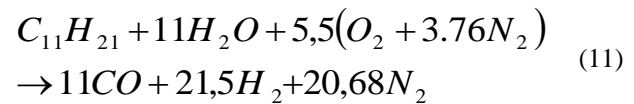
$$\eta_{CC} = \frac{FAR_{Theoretical}}{FAR_{Actual}} \tag{8}$$



Mathematical model used in heat exchanger is given in equation 10.

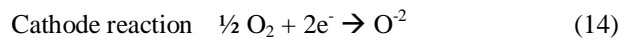
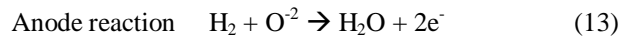
$$\epsilon_{HX} = \frac{T_2 - T_4}{T_{13} - T_{14}} \tag{10}$$

Mathematical model and chemical reaction used for jet fuel reformer are given in equations 11 and 12.



$$\eta_{H_2} = \frac{LHV_{H_2} \dot{n}_{H_2}}{LHV_{Fuel_6} \dot{n}_{Fuel_6} + Q_{JFR}} \tag{12}$$

Mathematical model, chemical and electrochemical reactions used for solid oxide fuel cell are given in equations 13 to 22.



$$V_{FC} = E_{Nernst} - \eta_{Conc} - \eta_{Act} - \eta_{Ohm} \tag{15}$$

$$E = E^0 - \frac{RT}{n_e F} \ln \left(\frac{P_{H_2} P_{O_2}^{1/2}}{P_{H_2O}} \right) \tag{16}$$

$$\eta_{Act} = \frac{RT}{2F} \ln \left(\frac{i}{i_L} \right) \tag{17}$$

$$\eta_{Ohm} = i \cdot \frac{L}{\sigma} \tag{18}$$

$$\eta_{Conc} = \frac{RT}{nF} \ln \left(\frac{i_L}{i_L - i} \right) \tag{19}$$

$$I_{YP} = nA \cdot F \cdot j \tag{20}$$

$$\dot{W}_{FC} = V_{FC} I_{FC} \tag{21}$$

$$\eta_{th,SOFC} = \frac{W_e}{HHV} = \frac{n_e FE}{HHV} \tag{22}$$

III. RESULTS AND CONCLUSIONS

Total system power and efficiency variation with compressor pressure ratio is given in Figure 2, where a typical gas turbine engine characteristic can be seen. The system's power peaks at the point where the gas turbine components operate at their design point conditions. The maximum efficiency is calculated as 33.2% for a CPR of 2.6 for the system in this study.

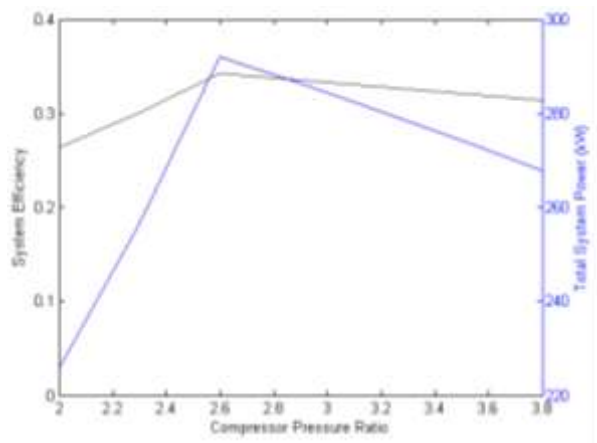


Fig. 2. Compressor Pressure Ratio – System Efficiency and Power

SOFC efficiency and power variation with CPR is given in figure 3. SOFC power increases with CPR while fuel cell efficiency is slightly decreasing. The increase in SOFC power is due to increase in the fuel and air flow rates with CPR. On the other hand, increase in the SOFC operating temperature leads to increase in activation loss, resulting in efficiency losses.

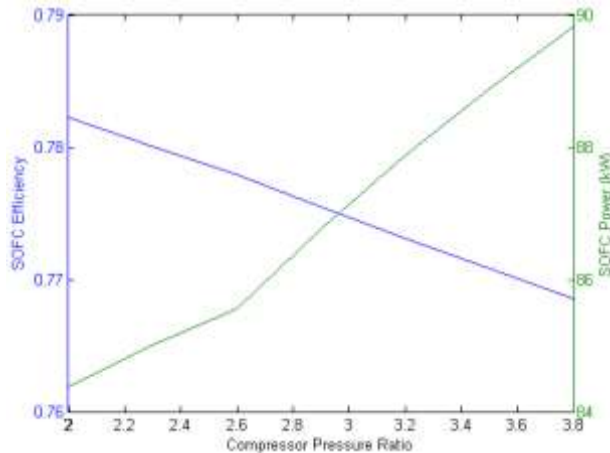


Fig. 3. SOFC efficiency and power variation with CPR

Gas turbine, SOFC and system power variation with CPR is given in Figure 4. The selected gas turbine’s maximum efficiency would be 23.2% if there wasn’t a SOFC in the system. The hybrid system’s maximum efficiency was increased up to 33.2% through the SOFC efficiencies of 76 to 78%.

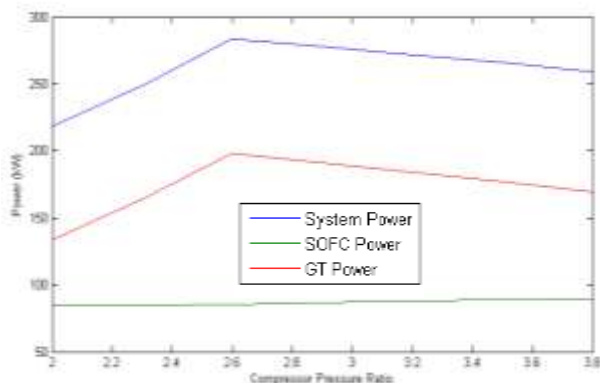


Fig. 4. Compressor Pressure Ratio – Power

The system’s fuel consumption and water production rate variation with CPR are given in Fig 5. The hybrid system’s fuel consumption is lower than the base gas turbine engine fuel consumption about 120 kg/h. The hybrid system’s fuel consumption is 61.8 kg/h and water production is 43.7 kg/h at the CPR of 2.6. As the system produces water at a rate of about 40.3 to 50.4 kg per hour, this much less water can be taken onboard before take-off, for each foreseen/planned flight hour of the aircraft.

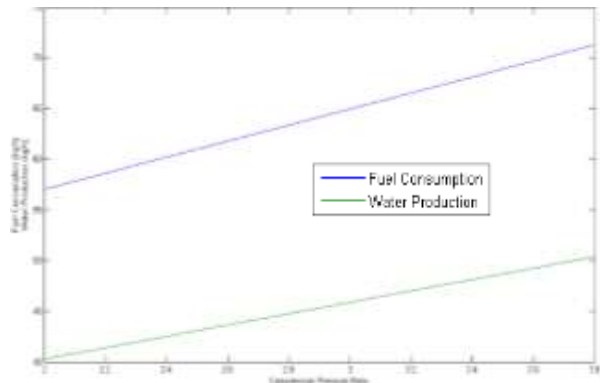


Fig. 5. Compressor Pressure Ratio – Fuel Consumption and Water Production

Increase in weights due to the additional components are shown in Table V.

TABLE V
GAS TURBINE APU – GT-SOFC HYBRID APU WEIGHT COMPARISON

Component	GT APU (kg)	State of the Art GT-SOFC APU (kg)	State of the Art Weight Difference (kg)
Gas Turbine (Honeywell 131/9A with 90 kW generator)	163.7	163.70	0,00
SOFC - 90 kW (700 W/kg)	0	128.57	128.57
Heat Exchanger	0	9.61	9.61
Jet Fuel Reformer	0	59.50	59.50
Water Tank for JFR	0	54,00	54,00
System Net Weight	163.7	415.38	251.68

The system’s total weight almost doubles with hybrid system. However, GT-SOFC hybrid system will consume 58.2 kg less fuel per hour with respect to the reference gas turbine APU, while producing 43.7 kg water per hour. This means, a total weight saving of 101.9 kg is possible per flight hour of the aircraft. Variation of the base and the hybrid APU influences on TOW of the aircraft are shown in Figure 6. In our case, the hybrid system recompenses for its weight increase in 2.47 hours of flight. It has to be noted that, the hybrid system will have less environmental effects, as it consumes less fuel than the conventional GT APU,

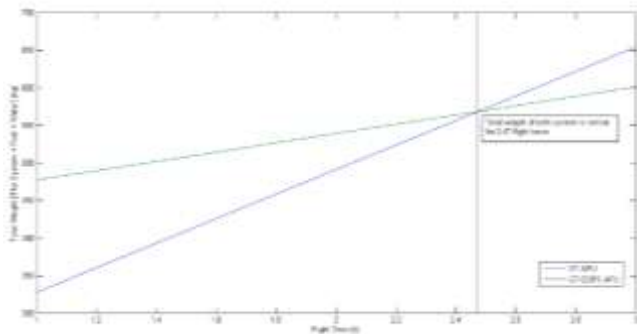


Fig. 6. Total weight variation with flight hour

Fuels for Aircrafts, Fuel Cells, More (All) Electric Aircraft, Unmanned Air Vehicles (UAV), Renewable Energy Sources and Technologies, Hydrogen Energy.

Mr. Tunca applied and granted for a government found (Turkish Republic Ministry of Science, Industry and Technology) which supports entrepreneurs and established his own company so as to develop aircraft maintenance equipments in 2015.

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