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Conceptual Design of a Hybrid Gas Turbine - Solid Oxide Fuel Cell System for Civil Aviation

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ABSTRACT

A conceptual design of a hybrid Gas Turbine - Solid Oxide Fuel Cell (SOFC) system is presented for civil aviation applications. The system operates using hydrogen as fuel, for the aircraft’s propulsion, while at the same time produces electrical energy in the fuel cell. Hydrogen is produced during flight by reformation of methane. The motivation of the study is to investigate hydrogen’s use for aviation purposes, so the hybrid system’s operation characteristics need to be examined. A configuration is designed, where a SOFC and the burner is modeled as one and simulated, in a modern multidisciplinary programming environment, in order to analyze the thermodynamic characteristics of the hybrid system. The fuel cell sets into motion when the aircraft reaches top of climb. During operation, liquefied natural gas is converted to hydrogen in the fuel cell and part of it is used to produce electrical energy while the rest for combustion. To determine the efficiency of the system, its performance was simulated using two scenarios, one for long-haul flights and one for short-haul flights. Comparing the results, for long-haul flights, the hybrid system presents a reduction in fuel consumption and an increase in thermal efficiency. For flights of a short range, the existing conditions in the fuel cell inlet were found to be prohibitive for it’s operation and the use of the hybrid system ineffective. For the system’s efficiency, the larger the pressure in the SOFC’s inlet the better. However, SOFC’s pressure limits restrict the pressure range and the cell’s use only during flight. Concluding, according to the study’s results, the hybrid system can operate in flight conditions, making the use of hydrogen in civil aviation possible. As a result, a 12% and 35% benefit is achieved, in fuel saving and thermal efficiency respectively.

Key words: Hybrid system; Solid Oxide Fuel Cell; Hydrogen; Fuel saving; thermal efficiency
**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Inlet surface (m²)</td>
</tr>
<tr>
<td>Cp</td>
<td>Specific heat in constant pressure (J/kgK)</td>
</tr>
<tr>
<td>f</td>
<td>Fuel to air ratio</td>
</tr>
<tr>
<td>F</td>
<td>Faraday’s constant (C/mol)</td>
</tr>
<tr>
<td>i_{an}</td>
<td>current density of anode (A/cm²)</td>
</tr>
<tr>
<td>i_{cat}</td>
<td>current density of cathode (A/cm²)</td>
</tr>
<tr>
<td>I</td>
<td>Current density (A/cm²)</td>
</tr>
<tr>
<td>m_f</td>
<td>Fuel mass flow rate (kg/s)</td>
</tr>
<tr>
<td>Ma</td>
<td>Mach number</td>
</tr>
<tr>
<td>M_{H2}</td>
<td>Molar mass of Hydrogen (kg/mol)</td>
</tr>
<tr>
<td>n_e</td>
<td>Number of electrons exchanged</td>
</tr>
<tr>
<td>P_i</td>
<td>Partial pressure</td>
</tr>
<tr>
<td>P_{HPC}</td>
<td>Pressure after the high pressure compressor (Pa)</td>
</tr>
<tr>
<td>r</td>
<td>Electrical resistance (Ω)</td>
</tr>
<tr>
<td>R</td>
<td>Gas constant (J/molK)</td>
</tr>
<tr>
<td>T</td>
<td>Temperature (K)</td>
</tr>
<tr>
<td>T_{HPC}</td>
<td>Temperature after the high-pressure compressor (K)</td>
</tr>
<tr>
<td>U_{in}</td>
<td>Inlet velocity (m/s)</td>
</tr>
<tr>
<td>U_{jet}</td>
<td>Jet velocity (m/s)</td>
</tr>
<tr>
<td>V</td>
<td>Voltage (V)</td>
</tr>
<tr>
<td>γ</td>
<td>Heat capacity ratio</td>
</tr>
<tr>
<td>ΔG</td>
<td>Gibbs energy</td>
</tr>
<tr>
<td>η</td>
<td>Adiabatic efficiency</td>
</tr>
<tr>
<td>η_{th}</td>
<td>Thermal efficiency</td>
</tr>
<tr>
<td>ρ</td>
<td>Density (kg/m³)</td>
</tr>
</tbody>
</table>

**ACRONYMS**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FU</td>
<td>Fuel Utilisation</td>
</tr>
<tr>
<td>LNG</td>
<td>Liquefied natural gas</td>
</tr>
<tr>
<td>PR</td>
<td>Pressure ratio</td>
</tr>
<tr>
<td>SF</td>
<td>Specific thrust</td>
</tr>
<tr>
<td>SFC</td>
<td>Specific fuel consumption</td>
</tr>
<tr>
<td>SOFC</td>
<td>Solid Oxide Fuel Cell</td>
</tr>
</tbody>
</table>
1.0 INTRODUCTION

From the start of the gas turbine’s use in aircraft engines, the improvement in turbomachinery’s efficiency has reached a level that is not expected to further increase in the next years. However, the combustion part that is responsible for fuel consumption and emissions, has not been developed as much and can be upgraded. The advancement efforts in aircraft engines are mainly focused in the produced noise, the used materials, the fuel consumption and the emissions part [1]. In addition, by comparing energy demand through the years, a rising trend in the use of natural resources has been noticed, with predictions for even higher energy consumption in the future [2]. On the other hand, due to dwindling fossil fuel resources and the environmental crisis an emerging need is observed for a cleaner and more efficient fuel to satisfy the impending changes.

Hydrogen could be the answer to this problem. Hydrogen is a renewable fuel that exists in abundance in earth’s atmosphere. It’s increased LHV gives rise to the turbine entering temperature providing higher efficiency [3]. Also, with the fuel’s high flammability range and flame velocity, lean combustion is succeeded with small residence time in the burner, reducing NOx emissions. In order to be used in aviation, it can be stored in cryogenic tanks placed above and behind the cabin of the aircraft [4], [5]. However, the small density of the fuel combined with the excess safety measures that are necessary for safe operation, make its use inefficient with nowadays technology.

To solve this problem an innovative hybrid system of a Gas Turbine and a Solid Oxide Fuel Cell (SOFC) is proposed for aviation. The SOFC can be used before the gas turbine’s burner, reforming hydrocarbon to hydrogen and at the same time generating electricity. SOFC is an electrochemical conversion device that produces electricity directly from oxidizing a fuel, in this case hydrogen. It derives its advantages from the electrolyte material used, providing high efficiency, stability, fuel flexibility, low emissions and relatively low cost [6]. In the last years, attempts have been made to insert this technology in aerospace applications, too [7], [8], [9], [10]. In this case, the combustion could take place with the unutilized fuel of the fuel cell and additional fuel if it is necessary. The hybrid system configuration includes a SOFC and a combustor modeled as one, so that heat exchangers can be neglected [11]. This method minimizes the total weight of the hybrid system and makes it suitable for aerospace applications, while at the same time produces electrical power contributing to the more electric aircraft concept [12], [13]. Solid oxide fuel cells coupled with micro-gas turbines are widely used for energy production, giving a substantial rise in the system’s efficiency [14], [15], [16], [17], [18], [19].

The scope of the current study is to introduce a hybrid Gas Turbine – Solid Oxide Fuel Cell system, in aviation, so that hydrogen can be used as a fuel in the burner, avoiding the disadvantages of its use. The thermodynamic characteristics of the system were determined by creating a computational model in modern multidisciplinary programming environment, where the system’s operation was simulated, in order to specify the system’s efficiency and viability.

2.0 METHODS

2.1 System’s configuration
It is already mentioned that the use of hydrogen creates certain problems in the flight planning. As an alternative fuel LNG is used for the engine’s operation. LNG consists predominantly of methane that in temperature above 500°C reacts with water and can be reformed to hydrogen. As a result, a reformer is set before the SOFC and the burner to ensure the use of hydrogen in the combustion without having the disadvantages of its use. The configuration proposed has a reformer that is circling the SOFC like a duct.

According to this configuration, the heat transfer between the fuel cell and the burner increases the system’s performance and ensures the necessary temperature for the reformation of methane. After the high-pressure compressor, a portion of the flow is led directly to the fuel cell’s cathode while the remainder is bypassed at the burner. The initial cell temperature is slightly higher than the intake flow, due to the heat transfer from the burner, then the reactions that take place in the fuel cell and the current generation further the temperature profile along the cell. On the other hand, the fuel inlet to the reformer is affected by both the heat transfer from the burner and the heat transfer from the exhaust flow of the cell. In this way, an average temperature of just over 500 °C is ensured in the reformer. Also, by modelling the fuel cell and the burner as one, the production of explosive mixtures of hydrogen with air is avoided and the electricity generated can contribute in the aircraft’s electrical load.

A thermodynamic analysis was carried out by creating a computational model in modern multidisciplinary programming environment (Matlab), so that the total efficiency and operation of the hybrid system can be presented. The simulation took into consideration a long-haul flight of 10 hours and a short-haul flight of 3-hours with inlet parameters according to Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Aircraft’s parameters for the two simulation scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 hours</td>
</tr>
<tr>
<td>Maximum Thrust</td>
<td>320 (kN)</td>
</tr>
<tr>
<td>Number of Engines</td>
<td>4</td>
</tr>
<tr>
<td>Overall Pressure Ratio</td>
<td>38</td>
</tr>
<tr>
<td>By-Pass Ratio</td>
<td>8.7</td>
</tr>
<tr>
<td>Fan Inlet Diameter</td>
<td>2.95 (m)</td>
</tr>
<tr>
<td>Maximum Take-off Weight</td>
<td>590 (tn)</td>
</tr>
<tr>
<td>Number of cells</td>
<td>2600</td>
</tr>
</tbody>
</table>

2.2 Aircraft’s mission simulation
For the flight’s simulation a computational model was created based on the thermodynamic analysis of the engine’s operation. The main equations used were:

Mass flow rate: \( \dot{m} = p A u_{in} \)  
(1)

Turbomachinery power: \( W = \dot{m} C_p \Delta T \)  
(2)

Temperature rise in compressor: \( T_i = T_{i-1} + \frac{\gamma - 1}{\eta} \frac{P_{PR}}{\gamma} \)  
(3)

Combustion power: \( W = m_i LHV \)  
(4)

Compressor - Turbine equilibrium: \( W_c = W_T \)  
(5)

Produced thrust: \( F = \dot{m} u_{jet} - \dot{m} u_{in} \)  
(6)

In velocities above 0.3M, where the flow starts to compress, the mass flow rate is calculated according to the non-dimensional mass flow rate, that is constant during the flight. Also, the thermodynamic analysis takes into consideration the additional thrust produced by the expansion of the flow in atmospheric conditions.

### 2.3 SOFC’s operation simulation

The computational model also simulates the operation of a pressurized SOFC according to the flight’s conditions. Pressurized SOFCs have been tested with an inlet pressure until 10-11 atm [20]. However, the compressed air after the high-pressure compressor can reach 40 atm. For this reason, the SOFC’s operation starts at the first top of climb, around 11000m, where the inlet air in the SOFC doesn’t exceed 10-11 atm. At takeoff, climb, descent and landing, only the reformer is in operation, using the temperature of the high compressed air and the heat transfer between reformer and combustor.

The main equations used were:

Current density: \( I = \frac{F u m_f + 2 F}{M_{H_2}} \)  
(7)

Ideal cell voltage: \( V_{Nernst} = \frac{\Delta G^0}{n_e F} + \frac{RT}{n_e F} \ln \frac{P_{H_2}}{P_{H_2O}} \)  
(8)

Activation losses: \( \Delta V_{act} = \frac{2RT}{n_e F} \sinh^{-1} \left( \frac{I}{j_{act}} \right) + \sinh^{-1} \left( \frac{I}{j_{act}} \right) \)  
(9)

Ohmic losses: \( \Delta V_{ohm} = I \cdot r \)  
(10)

Concentration losses: \( \Delta V_{conv} = m \cdot e^{ni} \)  
(11)

Voltage: \( V = V_{Nernst} - \Delta V_{act} - \Delta V_{ohm} - \Delta V_{conv} \)  
(12)

Electric Power: \( P = I \cdot V \)  
(13)

Temperature rise: \( \Delta T = 10^\circ C/cm \)  
(14)

Where concentration losses constants \( m = 10^{-4}, n = 8 \times 10^{-4} \).

In order to calculate the optimal fuel utilization, a number of iterations were made from 0.1-0.8. Firstly, the amount of fuel that needs to be burned in the combustor is determined, then the total fuel, current density and voltage are been accounted for every fuel utilization. The ideal fuel utilization is chosen when the current density is between 0.8 and 0.85 A/cm\(^2\) and the voltage also between 0.8 and 0.85 Volt.
Different SOFC geometries have been tested so that the best configuration of the hybrid system, that corresponds both in the efficiency of the Gas Turbine and the SOFC can be identified. The dimensions examined were taken according to the temperature limits of the fuel cell.

### 2.4 Accuracy of the model

For the verification of the results a comparison was made between the outputs of the typical engine at takeoff and top of climb and the AeroEngineS app [21] that was created in Aristotle University of Thessaloniki. After inserting the required inputs, the app calculates all the thermodynamic variables of an aircraft’s engine operation in a specific point during flight. The SOFC’s output was correlated with data from an academic software.

![Model's deviation](image)

In Fig 2 the model’s deviation is presented. It can be seen that most of the variables have an error below 4%. The maximum difference appears in the SFC, approximately 7%, possible due to the use of different constants and propagation error.

### 2.5 Order of Magnitude Analysis

An order of Magnitude Analysis was carried out so that the stability of the computational model can be observed. Imposing a small step change, from -2.5% to 2.5%, in the inlet parameters of the model, gave a different deviation each time in the thrust output that was later transformed into a function. The parameters examined regard the thermodynamic inlet parameters and the structural inlet parameters. In the first case, all the structural parameters of the engine remain constant and the thermodynamic are exposed to step changes. Then, with the thermodynamic parameters constant the structural variables are altered.

#### 2.5.1 Step change in TET

The step change imposed in the Turbine Entry Temperature (TET) of the model shows that each time the net thrust’s output and the model’s stability is not significantly altered.
The function that describes the TET’s step change effect in the output thrust was modeled as a polynomial of 9th grade. In order to depict the importance of its factor in the function the differences between the factors were plotted. Figure 3 shows that there is a big influence between zero and first order and a small nearly zero influence between the first and the rest factors, meaning that the changes in output thrust can be depicted with a linear function of TET’s step change.

\[ E = -1.66 \times 10^{-4} - 0.64x \]  

For an acceptance error of 0.01%, the error function according to TET step change is of \(Ox^2\) order of magnitude.

### 2.5.2 Step change in inlet diameter

The function of the change in output thrust with a step change in the inlet diameter is depicted in Fig 4. The step change imposed in the Inlet diameter of the model shows that each time the net thrust’s output has a bigger deviation than the corresponding step change. However, the deviation is not considered large enough to affect the stability of the model.

\[ E = -5.02 \times 10^{-4} - 2.17x + 0.038x^2 + 4.24 \times 10^3x^3 \]  

Figure 4 shows that there is a big influence between zero and first order, but also a significant influence of second and third order, meaning that the changes in output thrust can be depicted with a third order polynomial function of the imposed step change.
For an acceptance error of 0.01%, the error function according to inlet diameter step change is of $Ox^4$ order of magnitude.

3.0 RESULTS

As was already mentioned, the simulation took place in order to investigate the use of hydrogen for propulsion by analyzing the thermodynamic characteristics of the hybrid gas turbine solid oxide fuel cell system. The hybrid system configuration ensures hydrogen’s safe combustion in the burner, providing at the same time electrical power and propulsion. Two simulation scenarios were used, for long-haul and short-haul flights, in order to include the most common airline routes.

3.1 Long-haul flights

By plotting the velocity and altitude output of the computational model for the whole flight the envelope of flight is presented in Fig 5. According to Fig. 5 takeoff occurs in 0.28M and landing in 0.3M. Until 4000m, excess thrust is mainly consumed to increase the aircraft’s velocity, where from 4000m to 11000m the aircraft’s velocity and altitude are almost increased linearly. Then, as the aircraft reaches the tropopause, there is again a large acceleration until 0.85M which is later kept constant. During flight, when the aircraft’s weight has been significantly decreased due to fuel consumption, the altitude is increased so that the balance of forces in the vertical axis is secured.

![Figure 5: Envelope of flight for the hybrid system of a 30x30 stack size](image)

It needs to be mentioned that in order to compare the results for the different SOFC’s geometries and the typical engine, the increase in weight, as the SOFC gets bigger, is compensated with a decrease to the stored fuel. As a result, the aircraft’s takeoff weight stays the same in every configuration.
In Fig 6 the aircraft’s weight during the flight can be seen. It is clear that the configuration with the typical engine has a smaller landing weight than the hybrid cases. This is a result of two factors. The first regard the SOFC that is inserted in the hybrid configuration and gives rise to the total weight of the aircraft and the second and most substantial, regard the unused fuel that is stored in the aircraft when hydrogen is burned. On the other hand, when the SOFC stack is larger the rise in the inlet burner temperature is not enough to compensate for the increase of the aircraft’s weight and the fuel needed for optimal FU, so the total fuel used increases and the landing weight decreases. The fuel used in every configuration can be better understood in Fig 7, where the fuel saving is depicted compared to the fuel used in the typical engine.

Looking into the characteristics of the SOFC in Figs 8,9 can be seen, that with a greater stack size the electric power output and the efficiency of the hybrid system is showing a rising trend.
Also, the impact of the SOFC’s operation in the hybrid system is obvious in Fig 9. It should be highlighted herein that thermal efficiency has been normalised having as a reference the thermal efficiency of the conventional configuration during cruise. In the figure the thermal efficiency benefit increases the moment the SOFC starts to operate. At this point, it is clear that the longer the pressure limits that the SOFC can operate the better. Higher pressure inlet in the SOFC leads to longer period of operation, meaning higher thermal efficiency and fuel saving.

The rise in the output characteristics of the system can be explained from the increasing fuel utilization factor. As the size of the stack becomes larger, more fuel needs to be used in order to obtain the density current needed for optimal FU. This fact leads to higher fuel utilization, as shown in Fig 10, which increases the systems efficiency and provides with higher electric power output due to the size of the stack.
Concluding, two different trends have been observed from the configurations studied. As efficiency and output electric power tend to increase with the use of a larger stack, the fuel saving has an inverse trend. Therefore, in order to pinpoint the optimal stack size, the trends of these three parameters and their combined effect on the hybrid system has been calculated and depicted in Figs 11-12. From the combined trend, the optimal stack size appears to be in the diagram’s total extremum. Figure 12 depicts the optimal stack size for SOFC’s dimensions of 42x42 cm.

3.2 Short-haul flights

According to Fig 13 where the envelope of flight is presented, take off occurs at 0.3M and landing at 0.35M. Until 4000m, excess thrust is mainly consumed to increase the aircraft’s velocity, where from 4000m to 8500m the aircraft’s velocity and altitude are almost increased linearly. Then, there is again a large acceleration until 0.8M which is later kept constant.
For the simulation of a short-haul flight, the results showed a clear advantage in the fuel used for the flight. However, the flight’s altitude is lower than the long-haul flight and the compression ratio larger, making the pressure condition before the burner prohibitive for the SOFC to operate with nowadays technology. If hydrogen is used for combustion using only the reformer, without the SOFC, would create a complex, heavy system with questionable benefit. As a result, this configuration seems inefficient with current technology.

**4.0 CONCLUSIONS**

Having done the simulation of the operation of a hybrid Gas Turbine – Solid Oxide Fuel Cell system, that uses hydrogen in the combustor, it is understood that it is a promising system. From the results of the thermodynamic analysis, can be clarified that the operation of the hybrid system is a feasible and beneficial alternative as long as long-haul flights are concerned. The larger the pressure in the SOFC’s inlet he better, although SOFC’s pressure limits restrict the pressure range. Summarizing the results for:
Long-haul flights:

- Larger stack leads to an increase in output electrical power
- The fuel saving is inversely proportional to size of stack size
- As stack size grows, the optimal fuel utilization also grows resulting in an increase of engine thermal efficiency

Short-haul flights:

- Fuel saving that can reach 26%
- The fuel saving is inversely proportional to size of stack size
- Lower flight altitude and larger compression ratio make the pressure condition before the burner prohibitive for the SOFC to operate with current technology

By processing the results of non-dimensional power, efficiency and fuel saving, the optimal size of the SOFC was found to be 42x42 cm. The hybrid system can operate in flight condition’s, making the use of hydrogen in civil aviation possible, providing 12% and 35% in fuel saving and thermal efficiency respectively.

However, structural and experimental controls are still required to verify the viability and overall superiority of the hybrid system over current aviation engines. The further competitiveness of the hybrid system is related to the development of the SOFC materials. In this way, the cell can be used for higher pressure limits, thus longer flight time, inlet temperature and with increased current density without the risk of fast degradation of the fuel cell.

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