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# Electrochemical behavior and anode gas analysis of a planar SOFC via in-situ FTIR

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**Abstract.** This study conducts an experimental analysis of the electrochemical performance of a planar-type Solid Oxide Fuel Cell (SOFC) stack at temperatures of 650 °C, 700 °C, and 750 °C. The SOFC system, intended for principally for stationary applications, was assessed using a hydrogen/nitrogen fuel mixture. A thorough performance evaluation was conducted, encompassing polarization curves, power output, fuel utilization (FU), and area-specific resistance (ASR). Simultaneously, in situ Fourier Transform Infrared (FTIR) spectroscopy was utilized to analyze the composition of the anode exhaust gases. The findings indicate a significant improvement in power density, efficiency, and fuel conversion as temperature rises, which is linked to enhanced ionic conductivity and faster electrochemical kinetics. FTIR analysis confirmed the formation of near-stoichiometric water, aligning with theoretical predictions and validating the electrochemical reaction model. Furthermore, low levels of ammonia were observed at reduced current densities, indicating secondary reactions facilitated by the Ni-based anode. This integrated electrochemical-spectroscopic method offers insights into solid oxide fuel cell (SOFC) operation under realistic conditions and aids in the advancement of high-efficiency, low-emission energy systems for sustainable maritime applications.

## 1 Introduction

The global transition to low-carbon energy systems has increased the demand for efficient, environmentally friendly technologies to replace fossil fuel-based power generation. Solid Oxide Fuel Cells (SOFCs) stand out among the most promising solutions because they are highly electrically efficient (around 60% [1]), also they are flexible with fuel, as well as they are suitable for integration into combined heat and power (CHP) systems [2]. SOFCs can operate at high temperatures like 600-1000 °C and therefore ionic conductivity can improve while electrochemical reactions can occur fast plus they can utilize a wide range of fuels without any need for noble metal catalysts [3].

SOFCs attract growing attention in stationary applications and in decarbonizing the maritime sector [4]. In recent years, increasing regulatory pressure forces the maritime sector to reduce its greenhouse gas (GHG) and pollutant emissions. They can operate on hydrogen or low-carbon fuels, also since they are highly efficient and output few pollutants, SOFCs

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offer an interesting alternative to conventional marine diesel engines, particularly for auxiliary power units or hybrid propulsion systems [5].

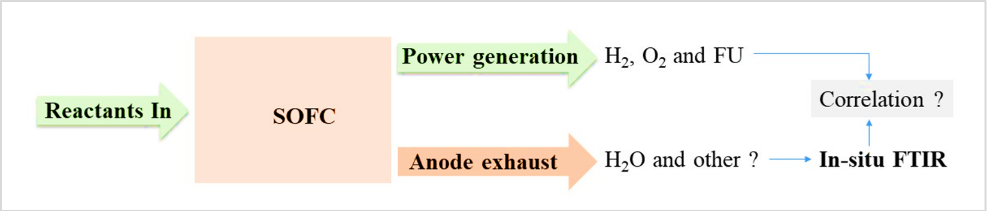
In spite of this important potential then, most studies until this date have focused mainly upon the electrical behavior plus performance for SOFCs, so they examined those polarization curves and power density with degradation mechanisms [6] [7]. Other researchers explored exhaust gases after treatment or energy recovery like their use inside catalytic burners [8]. However, in-situ experimental investigations into the exhaust gas composition remain limited under realistic operating conditions.

This paper discusses the experimental study on the electrochemical response of a planar-type SOFC stack fed with hydrogen as a fuel over a range of temperatures (650-750 °C). As well as polarization curve, power output, fuel utilization, and area specific resistance (ASR) analysis, in-situ Fourier Transform Infrared (FTIR) spectroscopy was used in order to measure the gas composition at the anode outlet. We will attempt to confirm that the water generation proceeds according to an electrochemical stoichiometry by comparing the consumption of hydrogen (as calculated from electrochemistry using Faraday's law) with the amount of water generated (detected by FTIR). This analysis can also be used to verify the correctness of both the methods of measurements and the reaction model assumptions. In addition, using the FTIR analysis, any non-predicted gaseous phase species can be identified. Overall, this integrated electrochemical-spectroscopic approach provides a first attempt to understand the SOFC behavior under varying operating conditions, and contributes to the optimization of fuel cell systems for sustainable energy applications, particularly in maritime environments where efficiency, reliability, and emissions control are of critical importance.

## 2 Methods

The experiments were carried out using a 1.8 kW SOFC stackbox (model G8-80) manufactured by SolydEra S.p.A. The fuel cell module consists of a stack composed of 70 anode-supported planar cells, each with an active area of 80 cm$^2$. The stackbox also includes integrated fuel and air manifolds, voltage acquisition and pressure ports, and heating panels to provide supplementary heat to the stack. The stackbox was connected to a custom-built test bench developed specifically for this application in our laboratory. The bench is equipped with two independent pre-heaters for fuel and air, as well as a gas conditioning system that regulates the inlet pressure and flow rates. An electronic load (EA-EL 9200-140 B from ES France) was used to monitor the electrochemical performance of the stack during operation. In addition, an FTIR instrument (FTX-ONE-CS from HORRIBA) was coupled to the anode outlet to enable in-situ analysis of the anode exhaust gases. The entire test bench was managed by an internally built LabVIEW program developed exclusively for the SOFC experiment. Its worthy to mention that the system was designed for stationary applications, particularly maritime transport.

The study was conducted at near ambient pressure and at three operating temperatures: 650 °C, 700 °C, and 750 °C. The fuel consisted of a hydrogen/nitrogen mixture, with 60 vol% of hydrogen, supplied at a total flow rate of 32.4 Nl/min and maintend constant (both $H_2$ and $N_2$ had a purity of 99.99%). Air was provided at a constant flow rate of 160 Nl/min. For each temperature, the stack current was ramped up and down at 5A/min within a safe range of voltage, from open-circuit voltage (OCV 89 V) to a minimum of 50 V, to avoid damaging the cells. At each temperature condition, the composition of the anode exhaust gas was continuously monitored via FTIR instrument, Scheme 1.




**Scheme 1**: Experimental methodology

# 3 Results & discussion

## 3.1 Effect of temperature on polarization curve and power

Figure 1(a) illustrates the relationship between voltage and power output as a function of current density across three distinct stack temperatures: 650 °C, 700 °C, and 750 °C. The polarization curves demonstrate a clear inverse relationship between voltage and current density, which is a fundamental characteristic of electrochemical energy systems. This behavior occur mainly because of internal irreversibilities like ohmic losses and mass transport constraints. At increased temperatures, higher current densities are noted for a specific voltage, suggesting enhanced cell performance. The linear region of the polarization curves, characterized by ohmic losses, exhibits a notable reduction in slope as temperature rises. The decrease in resistance results in a significant enhancement in power output, achieving almost 1700 W at 750 °C. Figure 1(b) illustrates the energy efficiency, derived from Equation (1), and plotted as a function of current density across various temperatures.

$$\textit{Energy efficiency} = \frac{\textit{Electrical power output (W)}}{H_2 \textit{ mass flow rate (kg/s)} * LHV_{H_2} \textit{(J/kg)}} \quad (1)$$

It is clear that increased efficiencies are attained at elevated operating temperatures for the same current density. At a temperature of 750 °C, the peak energy efficiency reaches approximately 48% at a current density of 0.43 $A.cm^{-2}$. A crucial aspect in analyzing fuel cell performance is the fuel utilization factor (FU), which is also known as fuel efficiency. This measures the ratio of the provided fuel that is successfully reacts to produce electricity. In this study, FU was calculated using Equation (2) [9].

$$FU = \frac{\textit{Stack current (A) * number of cells in the stack}}{\textit{Number of electrons per } H_2 \textit{ (i.e., 2) * Faraday's constant * Molar flow rate of hydrogen (mol/s)}} \quad (2)$$

Figure 1(c) illustrates that fuel utilization rises with current density at all temperature levels. It is important to note that elevated temperatures lead to improved fuel utilization at any specified current density, due to the acceleration of electrochemical kinetics and the minimization of internal losses. The curve at 750 °C attains the peak values, indicating a more effective fuel conversion process. The observations are intricately connected to the dynamics of Area-Specific Resistance (ASR). ASR serves as a valuable metric for assessing the total resistance of the fuel cell stack, which is represented through Ohm's law. Although it does not represent a tangible physical resistance, it accurately reflects the total ionic and electronic transport losses occurring within the electrolyte and the external circuitry. ASR proves to be especially beneficial for examining the linear segment of the V-I curve, where overpotential losses are predominant [10] [11] . Consequently, values at low current densities (below ~1 A) were omitted from ASR calculations, since this region is influenced by activation overpotentials that diverge from linear (ohmic) behavior. Then, ASR was calculated based on [12] and following equation 3.

$$ASR\ (\Omega.cm^2) = \frac{\text{Open circuit voltage (V) - Voltage (V)}}{\text{Current density (A/cm}^2\text{)}} \qquad (3)$$

Figure 1(c) presents the ASR trend in relation to energy efficiency across the three operating temperatures. A noticeable reduction in ASR is evident as temperature, fuel utilization, and efficiency rise. The findings are consistent with the previous analysis: in SOFCs, the ohmic drop frequently serves as the primary contributor to overpotential losses and is accurately depicted by the ASR. With an increase in temperature, there is a corresponding decrease in ASR, which results in lower voltage losses that align with the diminishing slope of the polarization curve illustrated in Figure 1(a). The positive impact of temperature on the electrochemical performance of the SOFC is clear. Increased operating temperatures improve ionic conductivity within the electrolyte, resulting in a reduction of the overall stack resistance. Furthermore, higher temperatures enhance reaction kinetics by lowering the activation energy needed for charge transfer and oxygen exchange, leading to increased fuel cell efficiency and power output. It is important to note that prolonged elevated operating temperatures might accelerate degradation phenomena such as nickel coarsening, interconnect oxidation, and seal fatigue [13]. A practical compromise is likely at 700°C, which offers significant performance enhancement relative to 600°C while reducing major long-term degradation risks projected at 750°C. Long-term studies will be essential to validate the optimal operating point.

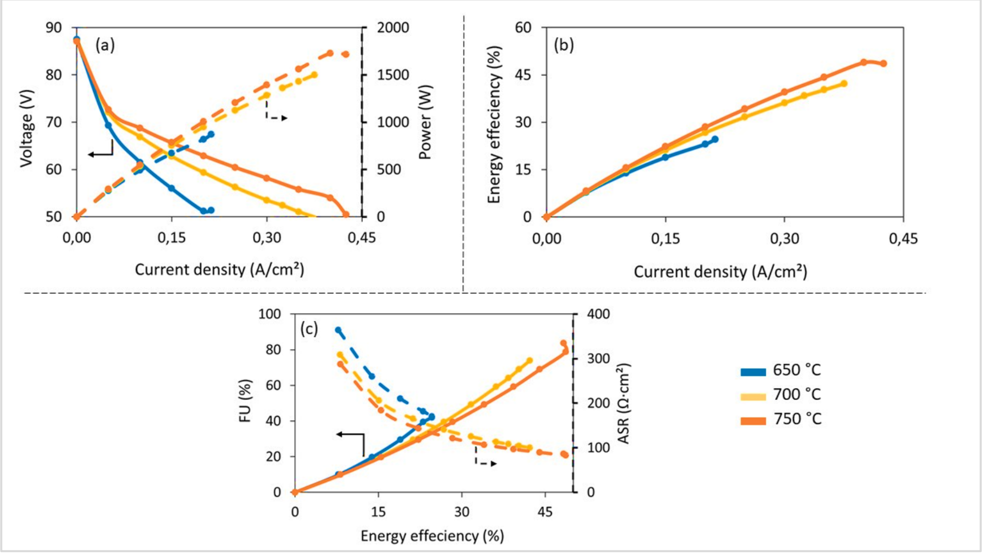



**Figure 1:** Electrochemical performance of the SOFC stack at different operating temperatures (650 °C, 700 °C, and 750 °C): (a) Voltage and power density versus current density; (b) Energy efficiency versus current density; (c) Fuel utilization versus current density and Area-Specific Resistance (ASR) versus energy efficiency.

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### 3.2 In-situ FTIR analysis

The exhaust gas analysis of a Solid Oxide Fuel Cell (SOFC) was performed using in situ Fourier Transform Infrared Spectroscopy (FTIR). This technique enables real-time identification and quantification of the main species present at the anode outlet, such as water vapor ($H_2O$), carbon dioxide ($CO_2$), carbon monoxide (CO), residual methane ($CH_4$), ammonia ($NH_3$), and other unconverted hydrocarbons. Thanks to its high sensitivity and multi-component detection capability, FTIR allows for the evaluation of operating conditions and the identification of potential secondary reactions or chemical imbalances within the cell. Under identical operating conditions and across various temperatures, the anode exhaust gases were analyzed to quantify the main products and verify the absence of unexpected species. A primary objective was to confirm that the stoichiometry of water formation was consistent with the expected electrochemical reaction. To achieve this, the amount of hydrogen and oxygen effectively consumed, calculated from the electrochemical data using Faraday's law, was compared with the quantity of water produced, as determined by in situ FTIR spectroscopy, Figure 2 (a-c). As expected, the results confirmed a nearly stoichiometric balance, reaction 1, with water yields matching theoretical values within a 93-95% range.

$$2H_2 + O_2 \longrightarrow 2H_2O \quad \text{(reaction 1)}$$

However, during the analysis, we unexpectedly detected traces of ammonia ($NH_3$). Its concentration decreased with increasing current density and water production, as shown in Figure 2(d). Although the $NH_3$ concentration remained very low compared to that of $H_2O$, its formation is primarily attributed to the thermally activated reaction between hydrogen and nitrogen. The Ni-based anode in the SOFC serves as a catalytic surface that promotes $NH_3$ synthesis. At low current densities, hydrogen remains abundant due to limited electrochemical consumption, thereby enabling this side reaction and the formation of ammonia. It is important to note that, although no significant degradation was detected during our short-term experiments, persistent $NH_3$ production could, in principle, compete for active nickel sites and potentially accelerate anode degradation during prolonged operation at low loads. To mitigate this risk, practical system operation should avoid extended durations in a low current environment. A long-term durability research would be necessary to quantitatively evaluate the effects of this side reaction.

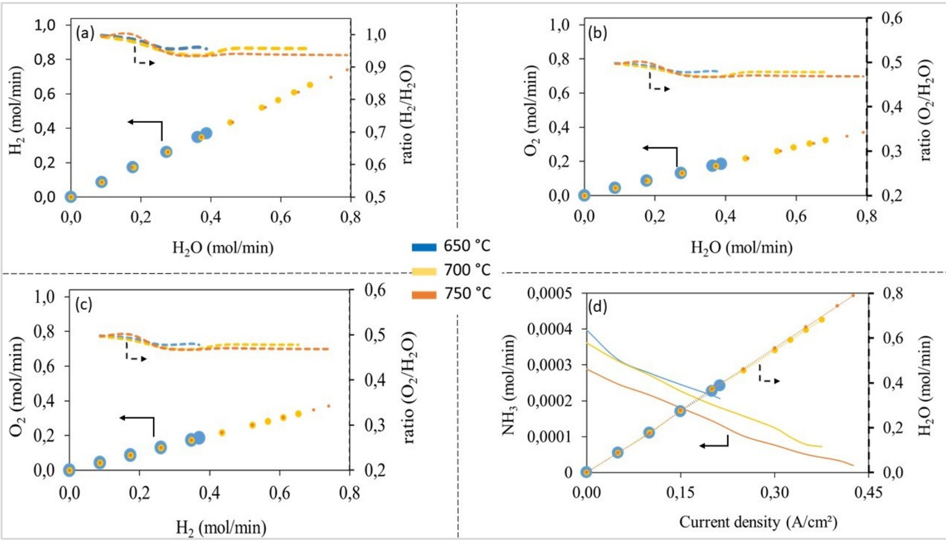


**Figure 2:** FTIR-based gas analysis at the SOFC anode outlet under various operating conditions: (a-c) Molar flow rates of $H_2$ and $O_2$, and their respective molar ratios ($H_2/H_2O$, $O_2/H_2O$, and $O_2/H_2$) as functions of $H_2O$ and $H_2$ flow rates; (d) $NH_3$ and $H_2O$ molar flow rates as functions of current density.

## 4 Conclusion

This study presents an experimental evaluation of the electrochemical performance of a planar-type solid oxide fuel cell stack, operated at different temperatures with hydrogen-rich fuel. The analysis indicated that elevated operating temperatures markedly enhance fuel cell efficiency, power output, and fuel utilization, attributed to improved ionic conductivity and accelerated electrochemical kinetics. The decrease in area-specific resistance (ASR) with increasing temperature further substantiates the performance improvements. The integration of in-situ FTIR spectroscopy enabled the successful quantification of exhaust gas composition at the anode outlet under real operating conditions. The findings confirmed the nearly stoichiometry of water formation as predicted by electrochemical calculations, thereby validating the measurement methods and the reaction model employed. The detection of ammonia at low current densities indicates the presence of secondary reactions, emphasizing the necessity of gas monitoring to optimize SOFC operation and mitigate potential emissions. This integrated electrochemical-spectroscopic method provides insights into SOFC performance and aids in the optimization of these systems for sustainable, low-emission and power generation.

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