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Experimental study on the long-term stability and thermal cycling endurance of micro-tubular solid oxide fuel cells and stacks using ammonia

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Abstract

Ammonia is a high-energy density, carbon-free, and easily transportable clean fuel, making it highly suitable for significant applications in portable and mobile scenarios when combined with micro-tubular solid oxide fuel cells (mTSOFCs). However, there is still a lack of research on the long-term stability and stack integration of mTSOFCs based on direct ammonia fuel. This study proposes a two-segment cell structure that effectively separates the ammonia decomposition and electrochemical reaction processes. The cell sample demonstrated good stability during continuous stable discharge for 1,039 h and 61 rapid thermal cycles. Furthermore, an 8-cell stack was constructed, achieving a peak power output of 30.89 W at 750 °C, with the ability to operate continuously for over 32.1 h and showing no significant degradation over 15 rapid thermal cycles, highlighting its potential for future applications.

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1. Introduction

Ammonia (NH₃) has attracted considerable attention as a carbon-free and high-hydrogen-content (17.8 wt.%) energy carrier because of its high energy density and easy liquefaction [1]. Unlike hydrogen, ammonia does not require low-temperature storage or high-pressure systems, making it an economical and efficient choice for energy storage and transportation [2,3]. Owing to their high efficiency and fuel flexibility, solid oxide fuel cells (SOFCs) are very suitable for direct utilization of NH₃ because they can utilize high operating temperatures (>700 °C) to achieve in situ NH₃ decomposition on the catalytic anode [4-12]. This avoids the need for an external NH3 cracking system and minimizes energy losses, thereby providing a simplified and efficient power generation approach [13]. These characteristics make NH₃-fueled SOFCs particularly suitable for portable and mobile power generation applications where compactness, low emissions, and high energy efficiency are critical [14].

Currently, researches on direct NH₃ fuel SOFCs have focused mainly on the long-term stability and thermal cycling stability of planar and flat-tubular SOFC cell units and stacks [1,15-17]. Planar and

flat-tubular SOFCs are known for their high-power density and scalability in stack design [18] and are suitable for large-scale power supplies and stationary applications. However, their long-term durability under harsh working conditions, especially rapid thermal cycling, remains a major challenge [15,18]. The micro-tubular SOFC (mTSOFC) is a configuration known for its high structural strength and resistance to thermal shock, making it suitable for portable and mobile applications [2,14,22]. There is still a lack of research and reports on the stability and stack integration and testing of directly NH₃-fed mTSOFCs [2].

Luo et al. [2] developed a tubular direct NH₃ solid oxide fuel cell with an output power exceeding 3 W and comprehensively studied the intrinsic processes combination through а of experimental measurements and multiphysics simulations. Jantakananuruk et al. [13] used 100 SCCM NH3 as fuel and obtained a maximum power of 12.2 W and a fuel utilization rate of 81 % at a high temperature of 800°C. Moreover, 150 hours of stability test confirmed the stability and durability of the tubular SOFC. Wang et al. [23] used a flat-tube SOFC with symmetric double-sided cathodes constantly fed with NH₃, which showed no apparent degradation

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after a 120 hr stability test at 750°C and maintained stable open-circuit voltages throughout 15 thermal cycles between 550 and 750°C. Recent experimental work using ammonia fuel SOFCs has reported on single-cell operation. However, stack-level performance and integration are still rarely explored. Notably, one of the main problems affecting planar and tubular configurations is anode degradation under NH₃. Nickel-based anodes commonly used in SOFCs are susceptible to chemical corrosion and poisoning by ammonia and its decomposition intermediates (such as new nitrogen and nitrides), resulting in long-term performance degradation and failure [1,16,23].

The nitridation reaction of ammonia at the anode of SOFCs significantly impacts cell performance and stability through multiple mechanisms. First, the reaction between Ni and NH₃ (Eq. (1)) results in the formation of nickel nitride (Ni₃N), which causes a volume expansion (approximately 20%) that leads to microstructural deformation, increased porosity, and a reduction in the number of active sites in the anode [13,19]. Electrochemically, Ni₃N – a thermally stable and electrically insulating phase-increases electrode polarization resistance by hindering gas diffusion and charge transfer [15]. Long-term operation exacerbates degradation through repeated nitridation-reduction cycles, which induce thermal stress and delamination at the anode-electrolyte interface, whereas Ni₃N coverage blocks active sites, suppressing NH₃ decomposition and H₂ oxidation [20]. The key factors influencing this process include temperature dependency (nitridation is favoured at <700°C, whereas high temperatures (>700°C) promote Ni₃N decomposition) [16], the NH₃ concentration (a high partial pressure enhances N adsorption on Ni surfaces) [21], and material interactions. Recent studies have shown that optimizing operating conditions (e.g., hightemperature operation), developing antinitridation materials (e.g., Ni-Fe alloys), and engineering electrolyte structures can effectively mitigate nitridation effects.

 $3Ni + NH_3 \rightarrow Ni_3N + 1.5H_2$ (Eq. 1)

To address the challenge of ammonia-induced anode degradation, most studies have focused on materialbased solutions [15]. Anode modification strategies, such as incorporating cerium-based promoters to increase catalytic activity or developing composite anode materials (e.g., perovskites or cermets), have been studied to better resist chemical erosion [16]. Zhu et al. [1], coupled a novel Ru-(BaO)₂(CaO)(Al₂O₃)(Ru-B₂CA) reversible NH₃ catalyst and achieved a maximum fuel cell power output of 877 mW/cm² at 650 °C with NH₃ fuel. Yang et al. [16] findings suggested that NH₃ pretreatment through thermal decomposition or the use of low-Ni or Ni-free ceramic anodes could suppress Ni nitriding in the Ni/YSZ anode. Hagen et al. [17] recommended operating at high fuel utilization (low flow rates) and elevated temperatures (\geq 750 °C) to achieve full NH₃ cracking and avoid nitridation in the SOFC anode. These methods have shown improve in reducing NH₃-induced degradation. However, their long-term effectiveness under stack-level operating conditions of thermal cycles is still uncertain. In addition, the dependence on material modification increases the complexity of manufacturing and scalability, highlighting the need for innovative system-level approaches to improve stability and durability.

In this work, we propose a novel two-stage structural mTSOFC design to address these challenges. This design effectively separated the ammonia decomposition process and the electrochemical reaction zone, thereby reducing the direct exposure of the anode to corrosive NH3 intermediates. The performance and durability of the proposed design were evaluated via extensive single-cell and stacklevel (8-cell) experiments, including long-term operation, rapid thermal cycling, and continuous stable discharge tests. The results showed that this method can improve the feasibility of ensuring the stability of the ammonia fuel SOFC system and may pave the way for practical applications of portable and mobile energy solutions.

2. Materials and Methods

2.1 Fabrication of the mTSOFC

The anode-supported mTSOFCs used in this study were prepared via extrusion and dip coating methods and were provided by Prof. Liang Bo from Guangdong University of Technology. The details of the material resources and sample manufacturing process can be found in previous works [24]. The appearances of the mTSOFCs are shown in Fig. 1 (a), with a total length of 160 mm and an outer diameter of 5.8 mm. The thicknesses of the anode (Ni/8YSZ), electrolyte (8YSZ), cathode interlayer (made of Gd_{0.1}Ce_{0.9}O_{1.95} (GDC)), and cathode (LSCF)/GDC) $(La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8})$ are approximately 560 µm, 5 µm, 1 µm, and 20 µm, respectively. The microstructure and thickness of the mTSOFC sample are shown in Fig. 2. The samples in this study were designed with a twosegment structure. Near the fuel entrance, there was a chemical reaction section (approximately 5.5 cm in length) outside the cathode layer, where the primary reaction was ammonia decomposition. Downstream was the electrochemical reaction section (approximately 10 cm in length), which was covered with a cathode layer, where the main



reaction was an electrochemical reaction. The appearance and schematic diagram of the mTSOFC samples are shown in Fig. 1 (b) and (c). At the end of the chemical reaction section, the electrolyte layer was polished to expose the inner anode. Silver wire was tightly wound around the polished area to collect the anode current. A coiled fine silver wire and a thin silver paste were applied to tightly cover the outer surface to collect current from the cathode. The total effective area of an mTSOFC sample was approximately 18.2 cm^2 .



Fig. 1. The structure of the mTSOFC: (a) appearance of the unpacked mTSOFC; (b) appearance of the packed mTSOFC; (c) schematic of the packed mTSOFC.



Fig. 2. Cross-sectional views of the mTSOFC sample: (a) overall appearance and (b) magnification near the electrolyte.

2.2 Fabrication of the mTSOFC stack

As shown in Fig. 3 (a), (b), (c) and (d), 8 mTSOFC unit samples were assembled into an 8-cell stack. The stack had a vertical structure, with a cylindrical gas distribution chamber at the bottom and a fuel inlet pipe centrally located at the top. The 8 mTSOFC unit samples were arranged in a circular symmetric manner on top of the gas distribution chamber and were fixed on the top of the chamber by ceramic glue. All 8 mTSOFC units were connected in series, and an annular ceramic chip was placed between each cell and the metal reactor wall for insulation. During the experimental tests, the fuel gas flowed from top to bottom into the gas distribution chamber and then from bottom to top into each mTSOFC unit. The total effective area of the stack is approximately 145.8 cm². Additionally, two air inlet pipes are symmetrically arranged inside the array of cell tubes, providing sufficient fresh air to the cathode side of the cells for the electrochemical reaction. A K-type thermocouple, isolated by a ceramic tube, is placed in the center of the cell array in the stack to obtain real-time temperature data during the testing process.





Fig. 3. The structure of the mTSOFC stack: (a) overall view, (b) sectional view, (c) vertical view of the schematic of the mTSOFC stack and (d) appearance of the mTSOFC stack.

2.3 Experimental procedure

A schematic diagram of the experimental setup is shown in Fig. 4. The experimental setup includes three main parts: a gas supply system, an mTSOFC operation system and a performance measuring system. The gas supply system provides hydrogen, ammonia, and air into the mTSOFC operation system by using mass flow controllers (Sevenstar Electronics Co. Ltd., China) to control the flow rate. During mTSOFC operation, an electric furnace is used to ensure relatively constant high-temperature operating conditions for a single unit or stack. At the outlet of a single unit or stack, exhaust fuel gas passes through a ceramic tube (Al₂O₃, 99%, approximately 4 cm long) and flows into the high-temperature hearth, where it is consumed by direct combustion to avoid potential danger caused by the emission of H₂ and NH₃. The performance measuring system included an electrochemical workstation (Gamry Reference 3000, Gamry, USA) and an electronic load (PLZ164WA, KIKUSUI Co. Ltd., Japan) for the electrochemical performance test.



Fig. 4. Schematic diagram of the experimental setup.

The mTSOFC samples and the 8-cell stack were placed in a tubular electric furnace for EIS, IV, and continuous discharge tests by an electrochemical workstation and an electronic load. The IV curves were obtained via a voltage scanning method initiated from the open-circuit voltage. The scanning rates were set at 10 mV/s for the mTSOFC samples and 80 mV/s for the 8-cell stack. For the EIS measurements of the mTSOFC samples, a voltage-controlled excitation method was employed with a



10-mV AC voltage perturbation superimposed on the open-circuit voltage, covering a frequency range from 100 kHz to 50 mHz. Since the 8 cells in the short stack were all in series mode, the discharge current of each cell was the same, so the EIS measurements for the 8-cell stack utilized a currentcontrolled excitation method with a 20 mA AC current perturbation superimposed on a 1 A DC operation current, spanning a frequency range of 20 kHz to 20 mHz. During the long-term continuous discharge test, the mTSOFC samples were operated in constant current mode, whereas the stack was operated in constant voltage mode. During the test of the mTSOFC samples, every 12 hours or 24 hours after discharge, the open circuit voltage was tested for 5 minutes, and the EIS curves were tested. During the thermal cycling tests, the mTSOFC samples were evaluated under a constant discharge current density of 0.1 A/cm², whereas the 8-cell stack was tested under open-circuit voltage conditions. Before the thermal cycling test, the electric heating furnace was heated to 700°C, and the cell sample was tested under a constant current discharge of 0.1 A/cm² until the voltage stabilized. At the beginning of a thermal cycle for the mTSOFC samples, heating was stopped first, and the furnace was cooled quickly and naturally. When the temperature decreased to 500°C, the temperature was turned on again, and the temperature in the furnace was raised again to 700°C within 5 min. The temperature program of the stack test was set as follows: after maintaining 700°C for 20 min, the temperature was set to 400°C within 10 min, then increased to 700°C within 10 min, and the temperature was maintained at 700°C for another 20 min

3. Results and discussion

3.1 Performance of the direct NH₃-fueled mTSOFC unit

First, the output performance of mTSOFC sampling was tested when hydrogen and ammonia were used as fuels at different temperatures (550~750°C). The results are shown in Fig. 5. At lower temperatures, when ammonia was used as a fuel, the performance of the mTSOFC sample was significantly lower than that when hydrogen was used as a fuel. The peak power density under NH3-fueled conditions at 550° C is 0.082 W/cm², which is only approximately 2/3 of that under H₂-fueled conditions (0.126) W/cm^2), as shown in Fig. 5 (a). With increasing temperature, the output performance of the mTSOFC sample under both fuel conditions improved, and the performance gap between using NH₃ and H₂ gradually narrowed. Above 650°C, the performance under these two conditions was almost the same, and the peak power densities at 750°C

were 0.208 W/cm² and 0.209 W/cm², respectively. This change was highly related to the indirect conversion process of NH₃ in the mTSOFC anode. On one hand, similar to the use of H₂ fuel, increasing the temperature accelerated the electrochemical reaction rate. On the other hand, the increase in temperature promotes ammonia decomposition, increasing the hydrogen content in the fuel, which improves the supply of reactants at the triple-phase boundary. According to the EIS-derived Nyquist plots, the ohmic resistance (R ohm) was identified as the leftmost intercept with the real axis (Z' axis) in the high-frequency region. The total resistance (*R* tot) was identified as the rightmost intercept with the real axis in the low-frequency region. The nonohmic resistance (*R_nonohm*) was calculated as $R_{tot} - R_{ohm}$, encompassing polarization losses and mass transport limitations. As shown in Fig. 5 (b) and (c), at lower temperatures, the nonohmic impedance of mTSOFC samples under NH₃-fueled conditions was significantly greater than that under H2-fueled conditions, especially in the highfrequency interval of the EIS test process, where the former showed significantly different impedance characteristics from the latter. Consistent with the findings of previous studies, this difference gradually disappeared above 650°C. As shown in Fig. 5 (d), with increasing temperature, the open circuit voltage (OCV) of the direct ammonia mTSOFC first increased and then decreased and gradually tended to be the same as that of hydrogen fuel. Moreover, insufficient NH₃ decomposition to produce H₂ at low temperatures was the main factor limiting its performance.

Next, the operational stability of the mTSOFC sample under NH₃-fueled condition was tested via long-term continuous discharge tests at 700°C, and the results are shown in Fig. 6. The discharge process was divided into two stages. In the first stage (0~206 h), the discharge current density was 0.1 A/cm^2 , and the output power decreased from 1.692 W to 1.687 W, with an average degradation rate of 1.43%/kh. In the second stage (206~1,039 h), the discharge current density was 0.2 A/cm², and the output power decreased from 2.844 W to 2.750 W, with an average degradation rate of 3.97%/kh. Figure 6 (a) shows the variations in the voltage and power density during discharge. Owing to the continuous consumption of NH₃, the supply pressure of the fuel storage tank was insufficient, and a sudden fuel shortage occurred for approximately 40 min when the discharge time reached approximately 357 h. As a result, the mTSOFC sample underwent a violent redox cycle, during which the minimum discharge voltage decreased to near 0 V. After the fuel gas supply was restored, the discharge voltage of the mTSOFC sample gradually recovered to a stable level within 20 min. This sudden fuel



starvation process had a significant effect on the performance of the cell. Since the exact time of fuel deficiency cannot be determined, the average power decay rates at 250-350 h and 360-660 h were compared, which were 1.98%/kh and 4.03%/kh, respectively. The intense redox cycle process caused faster degradation of the output performance, and the mechanism needs to be further researched. The variation in the OCV during the long-term discharge process is shown in Fig. 6 (b). In the initial period, the open-circuit voltage was quite stable and always maintained at approximately 1.112 V, indicating that the electrolyte layer of the mTSOFC and the ceramic glue at the connection were very dense, achieving a good gas seal effect. However, after the redox cycle,

the OCV of the cell significantly fluctuated, indicating the possibility of a very small gas leakage process. As shown in Fig. 6 (c), the primary reason for the increase in impedance before and after longterm discharge is the increase in ohmic resistance, which is attributed to the degradation of the silver paste layer in the cathode current collector [25]. As illustrated in Fig. 6 (d), the output power of the cell was fully restored to pre-interruption levels after fuel supply recovery, demonstrating the tolerance of the mTSOFCs in this study to drastic redox cycling. Although the degradation rate increased in Phase III, the system still exhibited comparatively superior discharge stability when benchmarked against prior studies on direct ammonia-fueled SOFCs [16,23].



Fig. 5. Performance of mTSOFC samples fuelled by hydrogen (flow rate: 90 SCCM) and ammonia (flow rate: 60 SCCM) at different temperatures. (a) I–V, I–P curves; (b) EIS curves; (c) impedance; (d) Open circuit voltage.

After more than 1,000 h of long-term discharge stability testing, the inner surfaces of the samples taken from different regions of the tested mTSOFC unit were characterized via SEM, and the resulting images are shown in Fig. 7. The inner surface of the upstream anode section, especially the region near fuel entrance. exhibited significant the agglomeration and severe corrosion of the Ni particles. These corrosion events were concentrated in the Inlet 1 region (approximately 2 cm long), and the downstream Inlet 2 region and electrochemical reaction sections were not significantly corroded, as

shown in Fig. 7 (b) - (i). The results of EDS characterization revealed that the nitrogen content of the corroded Ni particles increased significantly. The input of a high concentration of ammonia leads to the nitriding reaction between NH_3 and Ni, and the generated Ni_3N hinders the decomposition of NH_3 on the surface of the Ni metal particles. Compared with the results reported in the literature [16,23], the two-segment structure designed in this study effectively suppressed the impact of NH_3 -induced Ni nitridation on the anode electrochemical reaction, achieving better long-term stability.





Fig. 6. Continuous constant current discharge results of the mTSOFC sample: (a) Voltage and power density curves; (b) open-circuit voltage; (c) EIS curves; (d) voltage and power density variations before and after fuel supply interruption.



Fig. 7. SEM images of the inner surface of the anode after the long-term durability test in a NH₃ atmosphere. (a) Different positions of the samples at the mTSOFC; SEM images of the inlet (b) (c), transition section (d) (e), upstream working section (f) (g), and downstream working section (h) (i). Anode gas: NH₃ (flow rate: 60 SCCM); cathode gas: air (flow rate: 200 SCCM).

In portable applications, mTSOFCs need to undergo rapid start-stop processes and frequent changes in operating conditions, which always lead to rapid and drastic temperature changes, so mTSOFCs require excellent thermal shock resistance. In addition, when NH_3 is used as fuel, complex coupling of

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> endothermic decomposition reactions and exothermic electrochemical reactions occurs, and the influence on the robustness of mTSOFC units also needs to be verified. The rapid dynamic change process that mTSOFC units may face is usually simulated by setting a rapid change in the temperature of the heating furnace. The robustness and thermal shock resistance of the cell samples were verified through rapid thermal cycling, and the test results are shown in Fig. 8 (a). A complete thermal cycle process is shown in Fig. 8 (b). The mTSOFC sample underwent 8 thermal cycles under H₂ fuel and 53 thermal cycles under NH₃ fuel. The

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operating voltage decreased to approximately 0.4-0.5 V under H₂-fueled conditions as the temperature decreased during the thermal cycle. However, the lowest operating voltage at 500 °C is only 0.1-0.2 V under NH₃-fueled conditions because less H₂ is produced by the NH₃ decomposition reaction. After 61 consecutive rapid thermal cycles and 51 h of continuous discharge, the output power of the cell sample changed from 1.653 W to 1.702 W, with no significant degradation, as shown in Fig. 8 (a). Compared with the results reported in the literature [16,23], the cell samples and stacks in this study demonstrated excellent dynamic thermal stability.



Fig. 8. Rapid thermal cycle test results of the mTSOFC unit sample: (a) Voltage variation during 61 thermal cycles; (b) Voltage variation in a single thermal cycle.

3.2 Performance of the direct NH₃-fueled mTSOFC stack

The IV, IP and EIS curves of the 8-cell stack at different temperatures were tested, and the results are shown in Fig. 9. During the test, the inlet flows of H₂, NH₃ and air were 960 SCCM, 640 SCCM and 5400 SCCM, respectively. The OCV of the stack was maintained above 8 V, indicating good gas sealing characteristics of the stack. Similar to the test results of the mTSOFC unit, with increasing temperature, the performance of the stack under NH₃-fueled conditions gradually approached that under H₂-fueled conditions. The maximum output power of the stack under NH₃-fueled conditions at different temperatures was 15.253 W at 600 °C, 24.635 W at 650 °C, 27.498 W at 700 °C and 30.897 W at 750 °C, and the peak power density reached 212.2 mW/cm². The EIS test results are shown in Fig. 9 (b). At 750 °C, the ohmic resistance and nonohmic resistance of the stack were approximately 480 m Ω and 256 m Ω , respectively, whereas those of every mTSOFC unit were approximately 60 m Ω and 32 m Ω , respectively. The nonohmic resistance was similar to that of the mTSOFC unit, whereas the ohmic resistance was greater than that of the unit. This is due mainly to the

conduction resistance of the connecting line and the contact resistance at the connecting position between the mTSOFC units.

The operational stability of the 8-cell stack under NH₃-fueled conditions was tested via long-term continuous discharge tests at 700°C. Figure 10 (a) shows the changes in the output current and power of the stack during the 6 V constant-voltage discharge process. No obvious fluctuation or rapid attenuation occurred during the test. After 32.1 h of discharge, the output power changed from the initial 20.75 W to 20.54 W, with a voltage decrease of 1.01% and a power degradation rate of 0.312%/h, indicating a certain degree of stability. The EIS test results before and after continuous discharge are shown in Fig. 10 (b). The impedance of the stack increased from 820 m Ω to 832 m Ω , which was caused mainly by the ohmic impedance. A comprehensive inspection of the stack was conducted after the test. The silver paste on the cathode surface of several cell units for current collection evaporated and fell off at the position near the outlet, resulting in difficulties in current conduction in the exposed cathode area [25], which is consistent with the phenomenon observed during prolonged performance testing of the cell unit.





Fig. 9. (a) I–V and I–P characteristics and (b) EIS curves of mTSOFC samples fueled with hydrogen (flow rate: 960 SCCM) and ammonia (flow rate: 640 SCCM) at different temperatures.



Fig. 10. Continuous constant voltage discharge results of the 8-cell stack: (a) current and power variation curves and (b) EIS curves before and after the test.

Similar to the mTSOFC unit sample, a rapid thermal cycle test was carried out on the 8-cell stack to further verify the thermal shock resistance of the stack. During the thermal cycling process, the opencircuit voltage of the stack was continuously tested, and the results are shown in Fig. 11. The upper part of Fig. 11 shows the preset temperature program of the electric furnace and the real-time temperature of the stack collected by the K-type thermocouple. Owing to the limited heat dissipation rate in the furnace and the heat storage effect of the solid medium in the stack, during the rapid cooling process in the thermal cycle, the change in the actual stack temperature was slower than the set temperature, and the actual temperature cycled between 534 °C and 708 °C. The average heating rate during the thermal cycle was approximately 22

°C/min, whereas the average cooling rate was approximately 10 °C/min. The stack underwent 5 and 10 thermal cycles under H₂-fueled (960 SCCM) NH₃-fueled (640 SCCM) and conditions, respectively. The open-circuit voltage in the constant temperature section of the 8-cell stack was always maintained at approximately 8.50 V under both fuel conditions, and there was no obvious performance degradation, indicating good dynamic thermal stability. The EIS test results of the stack revealed that the total impedance was $860 \text{ m}\Omega$, 872m Ω and 896 m Ω before the thermal cycle test, after 5 cycles under H₂-fueled conditions and after 10 cycles under NH₃-fueled conditions, respectively. The total impedance after 15 thermal cycles only increased by 4.216%; that is, the impedance change rate was approximately 0.281% per thermal cycle.





Fig. 11. Rapid thermal cycle test results for the 8-cell stack.

4. Conclusion

On the basis of these results, the two-stage mTSOFC designed in this study can effectively utilize ammonia for stable long-term power generation, with an overall performance degradation of less than 3.5% over a testing period exceeding 1,000 hours. During the long-term test, the anode material in the inlet section effectively handled the ammonia, preventing damage to the anode in the electrochemical reaction zone. Compared with the use of additional catalyst layers, this approach reduces costs and simplifies the manufacturing process. The absence of an additional ammonia decomposition reactor component also facilitates system miniaturization, making it suitable for portable and mobile applications. As a carbon-free fuel, ammonia is a more suitable choice for future fuel than hydrocarbons such as methanol and LPG. The endothermic ammonia decomposition reaction occurring directly within the anode complements the exothermic electrochemical process, benefiting stack thermal management and achieving higher energy conversion efficiency. In the next phase of research, larger power mTSOFC stacks will be assembled, with improvements in current collector design to enhance long-term stack stability. Additionally, efforts will be made to better integrate functional components, design operational processes, and develop a fully integrated system.

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Conflicts of Interest

The authors declare that they have no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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