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हाइड्रोजन उत्पादन के लिए उच्च-तापमान वाष्प विद्युत अपघटन

High-Temperature Steam Electrolysis for Hydrogen Production

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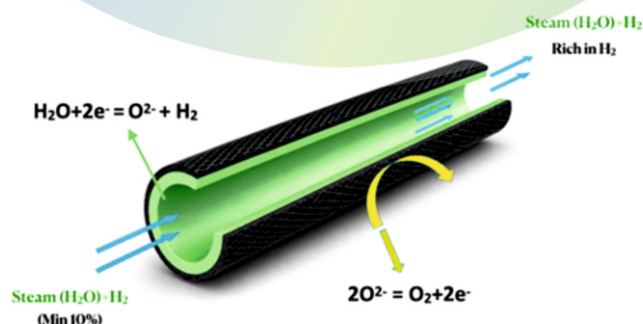
सारांश

ऊर्जा सुरक्षा, जीवाश्म ईंधन की कमी और हरित गृह गैस उत्सर्जन पर बढ़ती चिंताओं ने दीर्घकालिक हाइड्रोजन उत्पादन में रुचि बढ़ा दी है। ठोस ऑक्साइड विद्युत अपघटन सेलों (एसओईसी) का उपयोग करके उच्च तापमान वाले भाप विद्युत अपघटन (एचटीएसई) हाइड्रोजन उत्पादन के लिए सर्वाधिक ऊर्जा-कुशल तरीकों में से एक है। उत्पादित तापमान पर प्रचालन करते हुए, एचटीएसई वाष्प-विभाजन आवश्यकता के हिस्से की आपूर्ति के लिए तापीय ऊर्जा का उपयोग करता है, बिजली की खपत को कम करता है और कम तापमान वाले विद्युत अपघटन की तुलना में दक्षता में सुधार करता है। प्रौद्योगिकी को बड़े पैमाने पर हाइड्रोजन उत्पादन के लिए प्रगत परमाणु रिएक्टरों, केंद्रित सौर ताप प्रणालियों और औद्योगिक अपशिष्ट ऊष्मा स्रोतों के साथ प्रभावी ढंग से एकीकृत किया जा सकता है। भाभा परमाणु अनुसंधान केंद्र (बीएआरसी) में महत्वपूर्ण अनुसंधान एवं विकास प्रयासों ने ट्यूबलर एचटीएसई प्रौद्योगिकी पर ध्यान केंद्रित किया है। ट्यूबलर एसओईसी के लिए स्वदेशी विनिर्माण प्रौद्योगिकी को सफलतापूर्वक विकसित किया गया है, और 800 °C पर 150 घंटे से अधिक समय तक स्थिर प्रचालन का प्रदर्शन किया गया है, जिससे 4 NL h⁻¹ की औसत हाइड्रोजन उत्पादन दर प्राप्त हुई है। यह शोध पत्र एचटीएसई प्रौद्योगिकी की समीक्षा करता है, जिसमें प्रचालनीय सिद्धांतों, पदार्थों, स्टैक विन्यास और ट्यूबलर एसओईसी विकास में चुनौतियों पर ज़ोर दिया गया है।

ABSTRACT

Growing concerns over energy security, fossil fuel depletion, and greenhouse gas emissions have accelerated global interest in sustainable hydrogen production technologies. Hydrogen is widely regarded as a clean energy carrier because its utilization generates only water, making it a promising option for decarbonization of the energy and industrial sectors. However, most of the hydrogen currently produced worldwide is derived from fossil-fuel-based processes which are associated with considerable CO₂ emissions. Among various low-carbon hydrogen production routes, high-temperature steam electrolysis (HTSE) employing solid oxide electrolysis cells (SOECs) has emerged as one of the most energy-efficient electrochemical routes for hydrogen generation. HTSE operates at high temperatures, allowing part of the energy required for steam splitting to be supplied as heat instead of electricity. The favourable thermodynamics and faster electrochemical reactions at high temperatures reduce the electrical energy required for HTSE compared with low-temperature electrolysis systems. Furthermore, HTSE can be effectively integrated with advanced nuclear reactors, concentrated solar thermal systems, and industrial waste-heat sources for large-scale hydrogen production. R&D activities on tubular HTSE technology for hydrogen production applications have been undertaken at Bhabha Atomic Research Centre. Fabrication technology for tubular HTSE cells has been successfully developed, and stable long-term operation of tubular cells has been demonstrated for more than 150 h at 800°C, achieving an average hydrogen production rate of 4 NL h⁻¹. This paper reviews HTSE technology, focusing on operating principles, thermodynamic benefits, materials selection, stack configurations, and key challenges in tubular HTSE development.

KEYWORDS: HTSE; SOEC; Tubular electrolysis cells; Nuclear-coupled hydrogen production; Hydrogen energy



ट्यूबलर उच्च तापमान वाष्प विद्युत अपघटन
(एचटीएसई) सेल का चित्र।

A schematic of a tubular HTSE cell

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Introduction

Hydrogen has emerged as a promising zero-emission energy carrier capable of facilitating the global transition to clean energy. It offers several advantages, including high gravimetric energy density, long-term energy security, and the ability to mitigate the intermittency of renewable energy sources [1]. Fig.1 illustrates an integrated HTSE-SOFC hydrogen energy cycle. The process begins with green hydrogen production via steam electrolysis utilizing thermal and electrical energy derived from nuclear or concentrated solar power. The generated hydrogen can be stored in gaseous, liquid, or solid-state forms such as metal hydrides, which provide high storage density and improved safety. Stored hydrogen can later be utilized in fuel cells for the direct generation of electricity with high conversion efficiency and near-zero pollutant emissions. During fuel-cell operation, water or steam is produced as a by-product, thereby completing a sustainable hydrogen cycle. The integration of hydrogen production, storage, and utilization technologies is considered a key strategy for the development of future low-carbon energy infrastructures and sustainable energy systems.

Global hydrogen demand reached nearly 100 million tonnes in 2024, with the majority of hydrogen currently produced from fossil fuels, primarily through steam methane reforming (SMR). Conventional hydrogen production routes are associated with substantial greenhouse gas emissions, contributing approximately 900–1000 Mt CO₂-equivalent emissions annually. Despite increasing global emphasis on clean energy transition pathways, less than 1% of global hydrogen production presently originates from low-emission routes such as water electrolysis using renewable or nuclear electricity [2,3].

Among the available hydrogen production technologies, alkaline (ALK) and proton-exchange membrane (PEM) electrolysis are the most commercially mature. However, these systems operate at relatively low temperatures (20–80°C) and

require high electrical energy input, with typical specific energy consumption in the range of 50–55 kWh kg⁻¹ of H₂ produced [2–4]. In contrast, HTSE based on SOECs operates at 700–850°C, where part of the energy required for water splitting is supplied as heat instead of electricity. From a thermodynamic perspective, the enthalpy change (ΔH) for water splitting remains relatively constant at approximately 242–250 kJ mol⁻¹ over the HTSE operating range, whereas the Gibbs free energy change (ΔG), representing the minimum electrical work required for electrolysis, decreases significantly with increasing temperature. At 25°C, ΔG is approximately 237 kJ mol⁻¹, while at 800°C it decreases to nearly 180–190 kJ mol⁻¹. As a result, more energy can be supplied as heat, reducing the electrical energy requirement [4,5].

The thermodynamic advantage of HTSE is manifested through reduced operating cell voltage and lower electrical power consumption. The thermoneutral voltage decreases from approximately 1.48 V at room temperature to nearly 1.29–1.30 V at 800°C. As a result, HTSE systems require approximately 25–35% less electrical energy than conventional low-temperature electrolysis technologies [4]. When coupled with high-temperature heat sources such as advanced nuclear reactors or solar thermal systems, HTSE can achieve thermal-to-hydrogen efficiencies of 45–59% on a lower heating value (LHV) basis, making it a promising technology for large-scale low-carbon hydrogen production [5].

The Department of Atomic Energy (DAE) is pursuing R&D programs focused on the development of advanced high-temperature nuclear reactor technologies [6]. Integration of HTSE with advanced high-temperature reactor systems has the potential to expand the application of nuclear energy beyond electricity generation to efficient large-scale hydrogen production. The hydrogen generated through HTSE can be utilized in long-term energy storage and synthetic fuel production pathways, thereby supporting sustainable low-carbon energy systems.

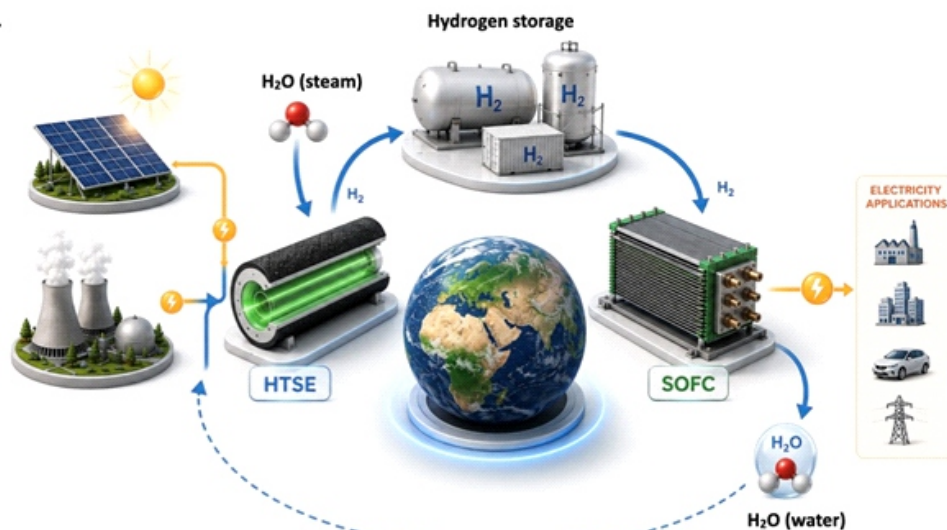


Fig.1: Schematic representation of an integrated HTSE-SOFC hydrogen energy cycle powered by renewable and nuclear energy sources.



Historical Development of HTSE Technology

The development of HTSE technology originated from early investigations on oxygen-ion-conducting ceramic electrolytes during 1960s. The development of stabilized zirconia electrolytes, particularly yttria-stabilized zirconia (YSZ), enabled operation above 800°C due to their high ionic conductivity and laid the foundation for SOFC and SOEC technologies. The global oil crisis of 1970s accelerated worldwide research on alternative energy technologies, including high-temperature electrochemical systems. During the late 1970s and 1980s, Westinghouse Electric Corporation pioneered the development of tubular SOFC architectures for elevated-temperature operation. The tubular configuration offered improved thermal shock resistance, simplified sealing requirements, and enhanced mechanical reliability, which later facilitated its adaptation for HTSE applications. Interest in HTSE increased after the 1990s because of growing focus on the hydrogen economy, renewable energy integration, nuclear-assisted hydrogen production, and decarbonization. Current research is focused on large-scale hydrogen production, reversible SOFC/SOEC systems, degradation mitigation, and integration with advanced nuclear reactors and renewable energy systems for efficient low-carbon hydrogen generation.

Operating Principles of SOFC and HTSE

SOFCs and HTSE systems operate through oxygen-ion transport across a dense ceramic electrolyte at 700–850°C. Both technologies employ similar cell architectures consisting of a porous fuel electrode, a dense oxygen-ion-conducting electrolyte, and an oxygen electrode, and are therefore considered reversible electrochemical systems. Fig.2 illustrates the operating principles of SOFCs and HTSE systems. In solid oxide fuel cell (SOFC) mode, chemical energy stored in fuels such as hydrogen is directly converted into electrical energy through electrochemical oxidation reactions. At the oxygen electrode, molecular oxygen undergoes electrochemical reduction to form oxygen ions, which subsequently migrate through the electrolyte toward the fuel electrode. At the fuel electrode, H₂

reacts with oxygen ions to produce steam while releasing electrons to the external circuit, thereby generating electrical power and heat.

In contrast, HTSE represents the reverse electrochemical operation of an SOFC. Instead of generating electricity, HTSE utilizes electrical energy and high-temperature steam to produce hydrogen through electrochemical steam reduction. At the steam/fuel electrode, steam undergoes electrochemical reduction to generate hydrogen and oxygen ions, while the oxygen ions migrate through the electrolyte toward the oxygen electrode, where oxygen evolution takes place. The electrolyte therefore serves both as an oxygen-ion conductor and as a gas-tight separator between the two electrode compartments. High operating temperatures improve reaction kinetics and oxygen-ion conductivity, reducing polarization losses and electrical power consumption.

Cell and Stack Geometries

HTSE systems are mainly classified into planar and tubular configurations (Fig.3), and the cell geometry strongly affects performance, thermal management, sealing, and durability. The planar geometry may be either electrolyte-supported, in which the electrolyte is thicker than the electrode layers, or electrode-supported, where one of the porous electrodes provides mechanical support for a thin electrolyte layer. Planar SOECs consist of flat multilayer ceramic cells assembled into stacks using metallic interconnects and high-temperature sealants. Their compact geometry provides high active-area utilization, short current collection paths, high volumetric efficiency, high power density, and reduced ohmic losses. Planar architectures are also well suited for large-area cell fabrication and scalable stack integration. However, these systems require complex high-temperature sealing arrangements and are more susceptible to thermo-mechanical stresses during operation and thermal cycling. The flat ceramic geometry further increases the risk of mechanical failure and gas leakage at sealing interfaces during prolonged high-temperature operation.

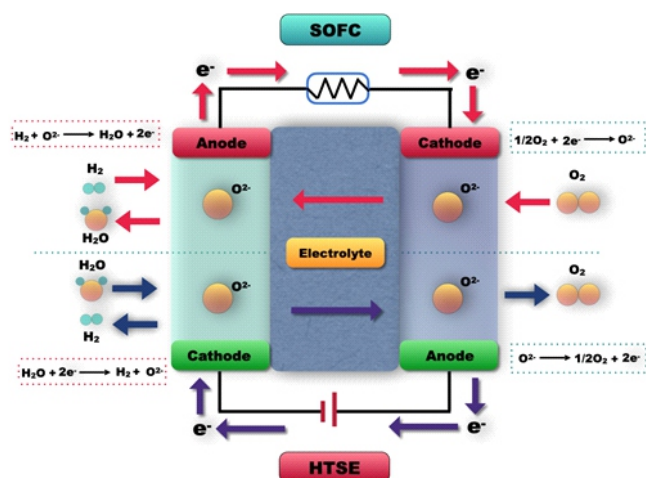


Fig.2: Schematic illustration of the operating principles of SOFC and HTSE, showing oxygen ion transport, electrode reactions, and electron flow during fuel cell and electrolysis modes.

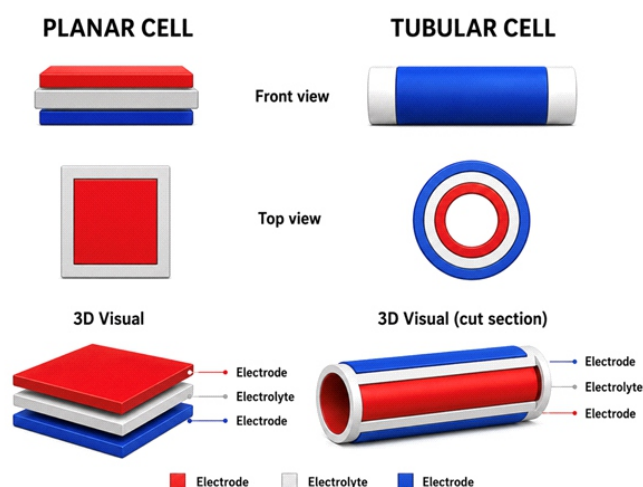


Fig.3: Schematic comparison of planar and tubular solid oxide cell configurations

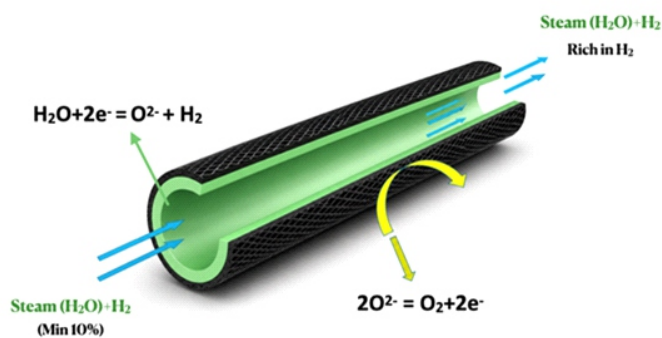


Fig.4: A schematic of a tubular HTSE cell.

Tubular HTSE cells comprise of cylindrical electrochemical structures in which electrode and electrolyte layers are concentrically deposited onto a tubular support. In the tubular configuration, one of the porous electrodes serves as the mechanical support tube on which a thin dense electrolyte layer is deposited, followed by deposition of the second porous electrode. Originally developed for tubular solid oxide fuel cells (SOFCs), this design was subsequently adapted for steam electrolysis applications. Tubular architectures offer superior thermal shock resistance, improved tolerance to thermal gradients and thermal cycling, simplified sealing requirements, and enhanced mechanical robustness. The tubular geometry reduces thermo-mechanical stress and gas leakage because fewer sealing joints are needed. These characteristics make tubular SOEC systems attractive for long-duration operation under harsh thermal environments and for nuclear-coupled HTSE applications requiring high thermal reliability. However, tubular HTSEs generally show lower power density and higher ohmic losses than planar designs because of longer current paths.



Components of Tubular HTSE and its Working Principle

HTSE is an all-solid-state electrochemical system in which both electrodes and the electrolyte are manufactured from ceramic-based materials. The most widely used electrolyte material for HTSE applications is yttria-stabilized zirconia (YSZ), owing to its excellent thermo-chemical stability and long-term operational reliability at elevated temperatures. The oxygen electrode is typically a perovskite oxide based on strontium-doped lanthanum manganite (LSM), whereas the fuel electrode generally consists of a porous Ni-YSZ cermet that provides both catalytic activity and electronic conductivity. HTSE stacks also require interconnects for electrical connection and high-temperature sealants for gas-tight operation. Interconnects are used for current collection and electrical connection between adjacent cells, while high-temperature sealants ensure hermetic separation between the fuel and oxygen compartments during prolonged high-temperature operation. The electrolyte layer must remain fully dense to prevent gas leakage and intermixing, whereas both electrode layers generally exhibit porosity in the range of 30–40 vol.% to facilitate gas transport and electrochemical reactions. The schematic of a tubular HTSE cell is shown in Fig.4. The tube is typically fabricated from porous NiO-YSZ material, over which a thin dense YSZ electrolyte layer is deposited, followed by coating of the Sr-doped lanthanum manganate (LSM) oxygen electrode. A mixture of steam and hydrogen is supplied to the fuel-electrode compartment of the tubular cell. A small amount of hydrogen (~10 vol.%) is added to maintain reducing conditions and prevent oxidation of the nickel electrode. During operation, a potential is applied between the two electrodes. At the fuel electrode, steam undergoes electrochemical reduction to generate hydrogen and oxygen ions. The oxygen ions are

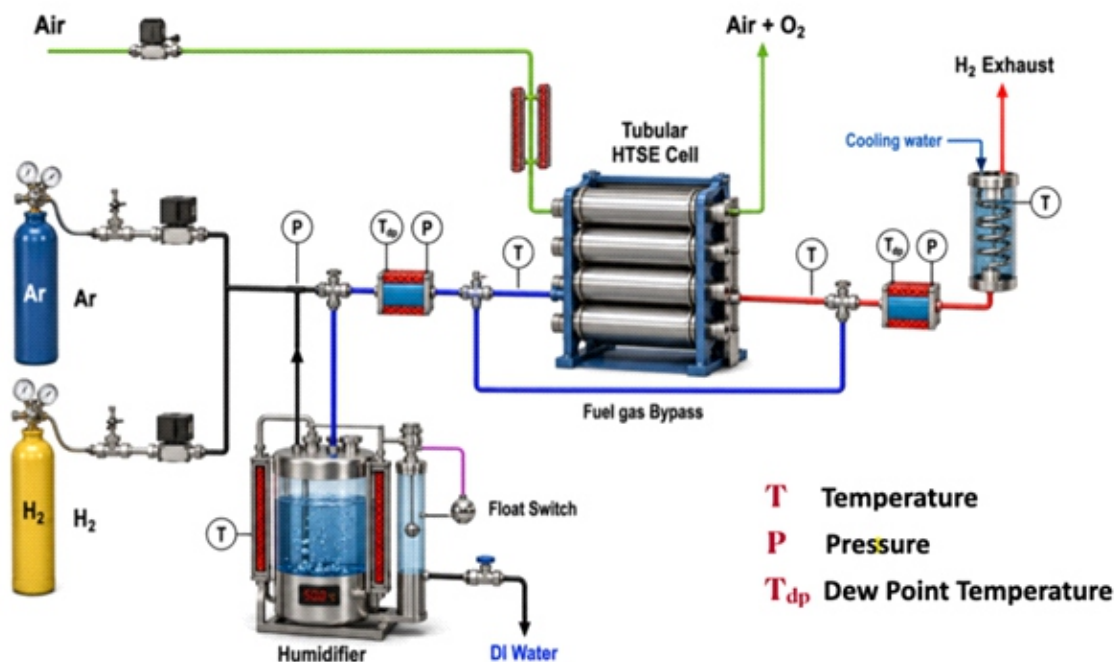


Fig.5: A schematic representation of test facility for electrochemical performance characterization of tubular HTSE cells.



Fig.6: Single Cell Tubular HTSE during long-term testing.

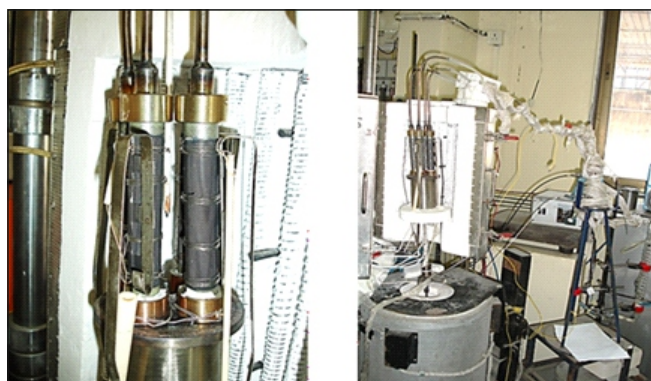


Fig.7: Multi-cell tubular HTSE assembly and testing.

subsequently transported through the dense oxygen-ion-conducting electrolyte under an applied electrical potential and are oxidized at the oxygen electrode to form molecular oxygen. During continuous electrolysis operation, hydrogen concentration within the fuel-electrode compartment progressively increases, while the outlet stream typically contains hydrogen together with unreacted steam. In HTSE operation, complete steam conversion is generally avoided to prevent steam starvation, electrode degradation, and concentration polarization. Consequently, downstream steam condensation or gas-separation processes are generally required to obtain high-purity hydrogen. Other important considerations in tubular HTSE systems include the long-term stability of sealants, electrical contact materials, and electrode-electrolyte interfaces under severe elevated-temperature redox conditions.



Current Status of HTSE development at BARC

At Bhabha Atomic Research Centre (BARC), fabrication technology for tubular HTSE cells has been successfully developed. A dedicated experimental facility for electrochemical performance characterization of tubular HTSE cells has been established [7]. A schematic representation of the test setup is shown in Fig.5. Using this facility, several long-term electrochemical performance studies of tubular HTSE cells were conducted. Under laboratory operating conditions, several tubular HTSE cells were operated continuously for 150 h at a current density of approximately 0.15 A cm^{-2} , corresponding to an average hydrogen production rate of about 4 NL h^{-1} (Fig.6). Electrochemical studies were conducted to evaluate the effects of temperature, steam flow rate, gas composition, electrical contact characteristics, and current density on hydrogen production [8,9]. To enhance the electrochemical performance of the tubular cell, the influence of various operating and process parameters on hydrogen production characteristics was systematically investigated through current density measurements. By optimizing the operating parameters, the tubular HTSE cells achieved a current density of 0.3 A cm^{-2} , which is generally considered a benchmark performance level for tubular HTSE systems reported in the literature. The studies showed that reducing interfacial and contact resistance is essential for improving hydrogen production and electrochemical efficiency. The investigations also indicated that electrical contact

degradation and thermo-mechanical instability at electrode-interconnect interfaces constitute important factors affecting long-term operational stability. Accordingly, ongoing research and development activities are focused on optimizing the electrical contact characteristics and interfacial stability of the cell components.

Following the successful demonstration of single tubular HTSE cell, fabrication and assembly of a four-cell tubular HTSE stack were undertaken. Fig.7 illustrates 4-cell HTSE Test assembly during electrochemical characterisation.

Preliminary long-term performance evaluations of the four-cell stack have shown encouraging results, while extended durability studies are currently in progress.

High-temperature glass sealants remain a major challenge because they must maintain sealing integrity, thermo-mechanical compatibility, and chemical stability under severe redox conditions.

Therefore, efforts were initiated toward the development of indigenous glass sealant materials suitable for HTSE and solid oxide fuel cell (SOFC) applications. Recently, an indigenous high-temperature glass sealant composition was successfully developed and evaluated under HTSE operating conditions. Long-term testing exceeding 300 h demonstrated satisfactory thermo-mechanical stability, chemical compatibility, and sealing integrity, indicating the suitability of the developed sealant for prolonged high-temperature operation.

Recent Developments in Nuclear-Coupled HTSE Systems

Recent studies have shown that hybrid nuclear-renewable-HTSE systems can improve grid stability and support flexible hydrogen production during periods of excess renewable power generation. Advanced reactor concepts, including High-Temperature Gas-Cooled Reactors (HTGRs), Small Modular Reactors (SMRs), molten salt reactors, and supercritical CO-cooled fast reactors, are being actively investigated for integrated hydrogen production applications. Thermodynamic analyses indicate that nuclear-assisted HTSE systems can achieve thermal-to-hydrogen efficiencies exceeding 50% under optimized operating conditions. Furthermore, optimized thermal integration, steam management, and waste heat recovery systems can further enhance overall plant efficiency and operational flexibility.



Recent studies have also demonstrated that hybrid nuclear-renewable-HTSE systems can improve grid stability and enable flexible hydrogen production during periods of excess renewable electricity generation [10-11]. Such hybrid systems offer promising solutions for seasonal energy storage and decarbonization of hard-to-abate industries.

Conclusions

Tubular HTSE represents a highly promising pathway for efficient and clean hydrogen production. Compared with conventional low-temperature electrolysis technologies, HTSE offers significantly higher thermodynamic efficiency because a substantial fraction of the energy required for steam splitting is supplied in the form of heat, thereby reducing electrical energy consumption. Tubular HTSE systems also offer advantages such as improved thermo-mechanical reliability, simpler sealing, better thermal cycling resistance, and higher structural stability. These characteristics make tubular HTSE systems attractive for integration with advanced nuclear reactors and renewable-energy-driven thermal systems.

India possesses substantial long-term strategic potential in nuclear-assisted hydrogen production because of its well-established nuclear energy programme, expertise in fast breeder reactor technology, and ongoing development of thorium-based nuclear systems. Integration of high-temperature nuclear reactors with tubular HTSE systems could enable large-scale green hydrogen production with low carbon emissions and support national energy security goals.

Developmental activities on tubular HTSE technology were initiated at Bhabha Atomic Research Centre, where fabrication technology for tubular HTSE cells has been successfully established. Stable long-term operation of a single tubular HTSE cell was demonstrated for more than 150 h at an operating temperature of 800°C, achieving an average hydrogen production rate of approximately 4 NL h⁻¹. In addition, development and long-term evaluation of a multi-cell tubular HTSE stack are currently in progress, with preliminary results indicating encouraging electrochemical performance and operational stability.

From the perspective of large-scale commercialization, further advances are required in the development of degradation-resistant electrode and interconnect materials, protective coatings against chromium volatilization, high-reliability sealing technologies, scalable ceramic manufacturing routes, and integrated thermal management strategies. Further research is required to mitigate long-term degradation caused by electrode delamination, nickel coarsening, chromium poisoning, redox instability, and thermal stress-induced cracking. Continued progress in these areas, together with system-level integration of HTSE with advanced nuclear and renewable energy sources, is expected to accelerate the deployment of sustainable hydrogen production technologies in the coming decades.

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