

Efficiency and oxygen permeability of Gadolinium doped Ceria for oxygen separation mechanism

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ABSTRACT

Our study investigates Gadolinium-doped ceria ($\text{Ce}_{0.90}\text{Gd}_{0.10}\text{O}_{1.95}$), a material extensively studied as a catalyst support and oxide-based ionic conductor in electrochemical devices. Fine powders were prepared for large-scale ceramics, achieving a green density of 50% and sintering density of 92% at 1200°C, significantly lower than prior temperatures. Impedance spectra analysis showed increased resistance at grain boundaries due to fine grain size, no longer observed above 600°C. Recent advances in ceramic membranes for oxygen separation highlight its distinct pathway from traditional methods, offering cost-effective synthesis of pure oxygen. Conductivity was temperature-dependent with distinct patterns. Activation energies for grain-boundary dissociation and complex dissociation were 1.2 eV and 0.1 eV, respectively, unaffected by grain boundary size. Further it highlights recent advancements in ceramic membranes for oxygen separation at elevated temperatures, addressing challenges in selectivity and efficiency. The presence of distortions or oxygen vacancies enhances its industrial value, offering exceptional oxygen storage properties and enabling efficient production through thermal swing processes with medium to low-temperature industrial waste heat. This research emphasizes $\text{Ce}_{0.90}\text{Gd}_{0.10}\text{O}_{1.95}$ industrial value due to distortions and oxygen vacancies, facilitating efficient oxygen production from air via thermal swing processes with medium to low-temperature industrial waste heat.

Introduction

The increasing demand for efficient and sustainable energy systems has catalyzed significant research into advanced materials capable of enhancing oxygen separation processes. Among the various materials investigated, Gadolinium-doped Ceria (GDC) has emerged as a promising candidate due to its unique combination of high ionic conductivity, thermal stability, and favorable redox properties (Shao *et al.*, 2000). These characteristics are particularly advantageous for applications such as solid oxide fuel cells (SOFCs), oxygen sensors, and membrane reactors, where effective oxygen ion transport is critical (Afzal and Khan, 2021).

Gadolinium-doped Ceria, a type of rare-earth-doped ceria (REDC), involves substituting cerium ions (Ce^{4+}) with gadolinium ions (Gd^{3+}), creating oxygen vacancies that enhance ionic conductivity (Liu *et al.*, 2013). The introduction of Gd^{3+} ions into the ceria lattice induces a local distortion and generates oxygen vacancies to maintain charge neutrality, significantly improving the material's ionic conductivity at intermediate temperatures (500-700°C). This makes GDC particularly suitable for intermediate-temperature applications, where it exhibits superior performance compared to other doped ceria materials (Shaula *et al.*, 2006).

The efficiency of GDC in oxygen separation mechanisms hinges on its ability to facilitate rapid oxygen ion transport while maintaining structural integrity under operational conditions. The efficiency of GDC in oxygen separation mechanisms is primarily determined by its oxygen permeability, which is a critical parameter for evaluating its performance in applications such as SOFCs and oxygen permeation membranes (Wei *et al.*, 2013). Oxygen permeability refers to the material's ability to allow oxygen ions to diffuse through its structure. High oxygen permeability is

essential for enhancing the performance of devices that rely on efficient oxygen ion conduction to achieve high power densities and operational efficiencies (Sunarso *et al.*, 2008). Oxygen permeability, a critical parameter for evaluating the performance of GDC in oxygen separation, is influenced by factors such as dopant concentration, operating temperature, and the micro structural properties of the material (Švarcová *et al.*, 2008). Higher oxygen permeability is desirable for enhancing the performance of devices like SOFCs and oxygen permeation membranes, which require efficient oxygen ion conduction to achieve high power densities and operational efficiencies (Subhadip Das, Rakesh Bhaskar, 2024). To design a large-scale hollow fiber membrane module for oxygen production, it's essential to conduct simulation studies on oxygen-permeable hollow fiber membrane modules. Additionally, one must consider heat and mass transfer along the radial direction of the hollow fiber. This comprehensive approach is necessary because the flow regime in the large reactor typically follows turbulent flow.

Oxygen-enriched air plays a crucial role in various sectors, including medical, chemical, and industrial fields. In the industrial sector, it finds application in enhancing combustion processes and improving air circulation, such as in sewerage treatment plants. By introducing oxygen-enriched air, combustion efficiency can be significantly enhanced, leading to better fuel burning efficiency, especially in internal combustion engines.

Oxygen, comprising approximately 21% of the air's volume, holds a prominent position among the top five commodity chemicals produced worldwide. Its significance lies in its extensive utilization across virtually every industrial sector, making it one of the most widely used commodity chemicals globally. The separation of oxygen from air constitutes a substantial industry, with an annual production of nearly 100 million tons of oxygen. This market for oxygen is anticipated to grow significantly in the future, driven by the increasing demand from large-scale clean energy technologies. These technologies, spanning sectors such as power generation, transportation, and manufacturing, rely on oxygen as a crucial feedstock for various processes, underscoring the vital role of oxygen production in facilitating sustainable development and innovation.

For instance, in a sewerage treatment plant, oxygen-enriched air can optimize microbial activity, aiding in the breakdown of organic matter and improving overall treatment efficiency. Similarly, in industrial processes requiring high-temperature combustion, such as steelmaking or glass production, oxygen enrichment can enhance combustion rates, resulting in energy savings and reduced emissions. The production of oxygen-enriched air is commonly achieved through two primary methods: cryogenic distillation and pressure swing adsorption (PSA). Cryogenic distillation involves cooling air to cryogenic temperatures to separate oxygen from other components, while PSA utilizes selective adsorption of nitrogen on adsorbent materials under pressure to produce oxygen-enriched streams. These methods offer flexible and efficient means to generate oxygen-enriched air for various industrial applications.

There are several significant uses for cerium and rare earth doped cerium powders, including abrasives, solid oxide fuel cell devices, gas chromatography, and catalysts (Plazaola *et al.*, 2019)(Cheng *et al.*, 2015). Cerium oxide exhibits a significant capacity to dissolve alkaline earth and rare earth oxides, resulting in the formation of solid solutions with alternating compositions. The presence of aliovalent cations leads to the creation of oxygen vacancies as a means of compensating for the charge, which in turn increases the ionic conductivity. At a temperature of 1400°C, gadolinium oxide exhibits complete solubility in ceria (Baker, 2002), and it possesses one of the greatest levels of ionic conductivity among these solid electrolytes (Balachandran *et al.*, 1997). Two primary methods for air separation have been established: cryogenic and non-cryogenic distillation. Cryogenic distillation is generally employed for applications demanding large quantities of ultra-low-temperature oxygen. The non-cryogenic method involves air separation at ambient temperatures, utilizing either molecular sieve adsorbents via pressure swing adsorption (PSA) or polymeric membranes in membrane separation processes. A new category of

air separation has recently surfaced, utilizing specialized ceramic membranes capable of separating oxygen from air at elevated temperatures. Because of the significant potential of ceramic-based membranes in oxygen separation from air, this paper aims to spotlight recent advancements in ceramic-based membranes for high-temperature oxygen-air separation. It will delve into issues and challenges concerning selectivity and separation performance. The process of oxygen transport through perovskite OPMs involves two primary steps: (i) oxygen exchange reaction on the membrane surface, including the adsorption and desorption of O₂, and (ii) bulk diffusion of oxygen in the form of ions or vacancies.

Gadolinium doped ceria is a kind of ceria-based solid solution that has been suggested for use in gas separation procedures at intermediate temperatures. These solid solutions may be produced by many methods, including typical powder mixing (Belaissaoui *et al.*, 2014)(Richter, Carlos and Beber, 2009), co-precipitation (Bouwmeester, 2003)(Capoen *et al.*, 2006)(Chen *et al.*, 1997), and hydrothermal recrystallization (Chen *et al.*, 1995). Chemical approaches often have an advantage over traditional procedures because to the strong reactivity of the precursor. Enabling a decrease in the temperature and duration of the sintering process. Prior studies (Aparicio-Anglès, Roldan and De Leeuw, 2015)(Chen *et al.*, 1996)(Cheng *et al.*, 2015)(Cook and Sammells, 1991) using polymeric precursor methods for fabricating ceria solid electrolytes have demonstrated that achieving high densification required the use of elevated temperatures (>1500°C) and extended durations (>5 h), or the inclusion of a milling process following calcination.

The oxygen permeation flux exhibits an inverse relationship with membrane thickness. Consequently, manufacturers are increasingly producing membranes with thicknesses on the order of tens of micrometers. An asymmetric structure is a prevalent design in membrane manufacturing, wherein thin dense membranes are supported on a porous substrate. This configuration offers several advantages, including mechanical strength provided by the porous substrate. The dense membrane layer facilitates selective permeation of oxygen molecules, while the porous substrate enhances structural integrity and facilitates gas transport across the membrane. By combining thin dense membranes with porous substrates, manufacturers can optimize both permeability and mechanical robustness, enabling the development of high-performance membranes for various applications, such as gas separation, purification, and membrane reactors.

The Gadolinium Cerium oxide solution was prepared using the above method. This approach offers the gain of being inexpensive and very uncomplicated. Furthermore, this method produces fewer carbon residues compared to other comparable synthesis procedures, and it has demonstrated significant efficacy in generating highly sinterable ceramic powders. The transport of oxygen across a membrane is facilitated through disparity of partial pressure or chemical potential of oxygen on either side (Bouwmeester and Burggraaf, 1996) (Chen *et al.*, 1996). Membrane technique demonstrates excellent energy efficiency and selectivity in producing very pure oxygen.

The potential of ceramic-based membranes for oxygen separation from air is indeed remarkable, offering a promising avenue for various industrial applications. In recent years, significant advancements have been made in this field, driving attention towards their efficacy, durability, and scalability.

This paper aims to delve into the latest developments in ceramic-based membranes tailored specifically for oxygen separation from air, particularly at high temperatures. By focusing on recent breakthroughs, we seek to shed light on the novel materials, fabrication techniques, and performance enhancements that have propelled the efficiency and feasibility of these membranes.

One area of notable progress is the refinement of ceramic materials with enhanced oxygen permeability and selectivity. Researchers have explored novel compositions, nanostructures, and surface modifications to optimize the transport properties of these membranes. Additionally,

advancements in fabrication techniques such as sol-gel processing, chemical vapor deposition, and templating methods have enabled precise control over membrane morphology and porosity, further enhancing their performance.

Furthermore, the integration of ceramic membranes into practical oxygen separation systems has been a key focus, with efforts directed towards scale-up, cost reduction, and operational reliability. Innovative reactor designs, membrane module configurations, and process integration strategies have been developed to address challenges related to pressure drop, membrane fouling, and thermal management, thereby facilitating the deployment of ceramic membranes in real-world applications.

Moreover, the utilization of ceramic membranes for oxygen separation holds promise across diverse industries, including but not limited to, oxy-fuel combustion, chemical synthesis, and medical oxygen generation. The ability to produce high-purity oxygen streams efficiently and economically has the potential to revolutionize these sectors, offering environmental benefits, process intensification, and enhanced product quality.

In summary, the recent advancements in ceramic-based membranes for oxygen separation from air represent a significant stride towards sustainable and efficient gas separation technologies. By exploring the latest innovations and challenges in this field, this paper aims to contribute to the broader understanding and utilization of ceramic membranes in various industrial applications.

Pure oxygen is extensively used in several fields such as medicine, organic chemistry, and the metal industry. The manufacture of it mostly depends on cryogenic separation, which is a well-established technology but is economically feasible only when done on a big scale. Technologies such as polymer membrane separation or swing adsorption, which are more compact, have not shown satisfactory levels of technical and economic efficiency. Nevertheless, employing compact ceramic membranes with combined oxygen ion and electron conductivity for separating oxygen from air at high temperatures offers an attractive option. This method also has the potential to be integrated with other technologies, such as catalytic partial oxidation of natural gas (methane) to produce syngas. Oxygen is a fundamental requirement for human life, especially highlighted by the significant demand during the global Covid-19 pandemic. This essential element serves various purposes in both chemical and medical fields. Currently, the primary method of oxygen supply involves transporting oxygen cylinders from oxygen generating stations. However, these cylinders are often large and heavy, posing challenges for transportation. Therefore, ensuring uninterrupted oxygen supply, particularly for hospitals, becomes imperative.

The efficacy of this approach hinges on the high levels of mixed conductivity and oxygen permeability achievable in oxides containing abundant labile oxygen vacancies and electro active metal cations. Among such oxides, the single-phase perovskite-like $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-d}$ has been extensively studied, but its susceptibility to structural instability prompts the exploration of alternative materials. In this regard, layered cobaltite's $LnBaCo_2O_{6-d}$, where Ln represents a rare earth element, have recently garnered attention. These compounds exhibit notable levels of both electron and oxygen ion conductivity.

Previous observations suggest that light doping of perovskite-related conductors with electrically inert aluminum cations may enhance robustness during reduction and improve oxygen transfer, while minimally affecting electron conduction. This strategy opens avenues for the development of more stable and efficient materials for oxygen separation."

Oxyfuel combustion, which involves burning fuel with pure oxygen rather than air, boasts high combustion efficiency due to its ability to conserve the sensible heat typically absorbed by the nitrogen in air. Moreover, oxyfuel combustion facilitates straightforward CO_2 separation from exhaust gases, thanks to the elevated concentrations of CO_2 and water vapor in the gas stream. Consequently, this technology is sought after as a novel foundation for industrial thermal processes, especially when combined with carbon capture and utilization. An air filter effectively removes harmful particles, including dust and humidity caused by environmental factors, down

to 0.3 microns in size. The compressor utilized to compress ambient air is a dry air compressor powered by a single electric motor. A pressure regulator then adjusts the pressure from the product tank to the oxygen mask within the range of 5 to 10 psi.

In this study, we will explore the efficiency and oxygen permeability of Gadolinium-doped Ceria for oxygen separation mechanisms. Experimental techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and electrochemical impedance spectroscopy (EIS) will be employed to characterize the synthesized GDC samples. Understanding the mechanisms underlying the oxygen permeability and efficiency of GDC not only advances the material science of doped ceria but also contributes to the broader field of energy conversion and storage technologies.

Over the past two decades, there has been a notable surge in interest surrounding perovskite Ion Transport Membrane (ITM) membranes, particularly those configured in a hollow fiber format and fabricated through the phase inversion/sintering technique. These membranes have garnered significant attention due to their distinct advantages over conventional planar and tubular membrane configurations.

One of the key advantages of hollow fiber ITM membranes is their larger surface area-to-volume ratio. This characteristic allows for more efficient gas-solid interactions, resulting in enhanced oxygen permeation rates. Additionally, the hollow fiber geometry enables the fabrication of membranes with finer structures, leading to improved selectivity and overall performance.

The phase inversion/sintering technique used in the fabrication process offers several benefits, including precise control over membrane morphology and pore structure. This technique allows for the formation of dense, defect-free membranes with uniform pore distribution, which are crucial for achieving high oxygen permeation rates and long-term stability.

Overall, hollow fiber ITM membranes fabricated using the phase inversion/sintering technique represent a promising advancement in membrane technology. Their superior performance characteristics make them well-suited for a wide range of applications, including oxygen separation, gas purification, and energy production.

Literature Review

Afzal, S., & Khan, A. (2021). Recent Advances in Molten-Carbonate Membranes for Carbon Dioxide Separation: Focus on Material Selection, Geometry, and Surface Modification. *Scientific World Journal*, 2021 stipulates Recent advancements in molten-carbonate (MC) membranes have shown promising potential for carbon dioxide (CO_2) separation, focusing on material selection, membrane geometry, and surface modifications. This review categorizes MC membranes into three types based on mechanisms: Mixed Electronically and Ionically Conducting Ceramics (MECC), Mixed Oxide and Carbonate Ceramics (MOCC), and Mixed Electronically and Oxygen-Ion Conducting Ceramics (MEOCC). Membranes are chosen for their ability to tailor intrinsic properties like selectivity, permeability, and scalability through optimized fabrication methods and operational conditions. MECC, MOCC, and MEOCC membranes offer varying advantages depending on the specific application requirements, such as high temperature stability and chemical resistance (Afzal & Khan, 2021).

The performance of MC membranes is significantly influenced by their physical properties, including support microstructure, membrane geometry, and thickness. These factors affect CO_2 permeation rates and selectivity, making them crucial considerations in membrane design and optimization (Afzal & Khan, 2021).

Despite their promise, MC membranes face challenges such as long-term stability at high temperatures, scalability to commercial levels, and cost-effectiveness. Addressing these challenges

requires systematic approaches including the selection of alternative materials and integration of advanced fabrication techniques such as Atomic Layer Deposition (ALD) for surface modifications. These efforts aim to enhance CO_2 permeation efficiency and ensure chemical stability under real-world conditions (Afzal & Khan, 2021).

In conclusion, MC membranes represent a significant advancement in CO_2 separation technologies, offering customizable properties that can be optimized for various industrial applications. Continued research and development are essential to overcome current challenges and facilitate widespread adoption of MC membranes in CO_2 capture and other environmentally beneficial processes.

Aparicio-Anglès, X., Roldan, A. and De Leeuw, N.H. (2015) ‘Gadolinium-Vacancy Clusters in the (111) Surface of Gadolinium-Doped Ceria: A Density Functional Theory Study’, *Chemistry of Materials*, 27(23), pp. 7910–7917. Reviews the Research employing DFT+U techniques has thoroughly investigated the behavior of gadolinium-doped ceria (GDC) (111) surfaces, focusing on various dopant distributions and their implications for solid oxide fuel cell (SOFC) applications. At a dopant concentration of 6.67%, the study found no distinct preference for the location of gadolinium (Gd) atoms within the ceria lattice. However, oxygen vacancies (VO) predominantly occupy the oxygen sub-layer, positioned at either the nearest or next nearest neighbor site relative to Gd. This positioning is facilitated by surface relaxation mechanisms.

Energies associated with dopant segregation suggest that defect clusters are stabilized thermodynamically at the surface. Importantly, under SOFC operating temperatures, analysis indicates a diversity of Gd-VO configurations due to configurational entropy. This diversity suggests that a mixture of different Gd-VO clusters is likely present.

Furthermore, the study reveals enhanced oxygen vacancy mobility with lower activation energies when vacancies move from the surface to the second oxygen layer. This directional preference in oxygen diffusion explains the tendency for vacancies to be trapped near the interface in the presence of Gd clusters.

Increasing the gadolinium concentration did not significantly alter the geometry or electronic structure. However, considering configurational entropy and temperature effects revealed a dominant dopant cluster at higher concentrations. This observation aligns with experimental findings indicating the formation of dopant domains near the surface under high dopant concentrations.

In summary, the research underscores the significant role of configurational contributions in doped ceria systems. The identified segregation of dopants and vacancies to the surface provides valuable insights for the design of new materials and processes in SOFC technology, highlighting avenues for enhancing performance and efficiency.

This study contributes to advancing understanding and optimizing the utilization of GDC in energy applications, particularly in enhancing oxygen ion transport and overall SOFC performance.

Shaula, A.L. *et al.* (2006) ‘Oxygen permeability of mixed-conducting composite membranes: Effects of phase interaction’, *Journal of Solid State Electrochemistry*, 10(1), pp. 28–40 stated that the use of membranes in separating natural gas mixtures is expected to become the largest application in the next 10-20 years. Untreated natural gas contains contaminants like oil mist, glycol, methanol, and iron sulfide particulates, necessitating thorough pretreatment for safe membrane operation, especially with hollow-fiber membranes. Early equipment faced fouling issues due to inadequate pretreatment, which modern plants now mitigate with extensive pretreatment processes, albeit at higher costs. As more selective and fouling-resistant membranes are developed, this market is poised to expand.

Current units use cellulose acetate membranes with a CO_2 /methane selectivity of 15. Replacing these with polyimides or polyaramides boasting selectivities of 20-25 could increase membrane market share. Laboratory studies have shown membrane materials with selectivities up to 40, suggesting potential for replacing most amine plants pending scale-up and commercialization.

New membrane applications include NGL separation, dehydration of natural gas, and nitrogen removal, with significant growth anticipated in offshore platforms and small, remote plants where membrane technology excels.

Ceramic and carbon fiber membranes are less promising for noncondensable gas separation due to their higher cost (10-100 times more than polymeric membranes). Their advantage lies in high-temperature separation of hydrocarbon vapor/vapor mixtures where they compete with distillation. Applications such as alcohol dehydration in vapor phase are feasible with ceramic membranes, with potential for ion-conducting membrane reactors as a specialized category.

The membrane market is forecasted to grow significantly, reaching \$350 million by 2010 and doubling again to \$760 million by 2020, driven largely by new applications in hydrocarbon vapor separations. While polymeric membranes will be used in some applications, future growth may see new materials like ceramics, carbon fibers, or hybrid inorganic/polymeric membranes gaining traction.

Balachandran, U. *et al.* (1997) 'Ceramic membrane reactor for converting methane to syngas', *Catalysis Today*, 36(3), pp. 265–272 reviews mixed-conducting ceramic materials derived from mixed-oxide systems, specifically of the Sr-Fe-Co-O (SFC) type, have been successfully synthesized into tube and bar forms. These materials underwent thorough investigation to assess their thermodynamic stability under varying oxygen partial pressures using high-temperature X-ray diffraction (XRD). The mechanical properties of SFC⁻², a specific variant of these ceramics, were found to be suitable for use in reactors, highlighting their robustness and reliability in practical applications.

In addition to their structural integrity, these materials exhibit noteworthy electronic and ionic conductivity properties. These characteristics are crucial for their performance in various electrochemical applications, where efficient transport of both electrons and ions is essential for optimal functionality.

This research underscores the advancement and potential of mixed-conducting ceramic materials like SFC variants, positioning them as promising candidates for applications requiring high-temperature stability, mechanical durability, and excellent electronic and ionic transport properties.

Belaissaoui, B. *et al.* (2014) 'Energy efficiency of oxygen enriched air production technologies: Cryogeny vs. membranes', *Energy Procedia*, 63(0), pp. 497–503 reviews membranes are frequently touted as a promising technology in oxygen-enriched air (OEA) production, with claims suggesting potential energy savings up to 50% compared to traditional methods like cryogenic distillation [4], [38]. This study aimed to provide a comprehensive comparison of membrane-based processes versus cryogenic distillation in terms of energy efficiency, focusing particularly on the impact of advanced membrane materials with enhanced selectivity.

The evaluation highlighted several key findings:

Energy Efficiency Comparison Membrane technologies indeed show promising potential to significantly reduce energy consumption compared to cryogenic distillation methods. This advantage stems from the lower energy requirements associated with membrane processes, which primarily involve gas separation through selective permeation across a membrane material, as opposed to the energy-intensive cooling and distillation processes required in cryogenic systems.

Impact of Improved Membrane Materials: The study underscored the critical role of membrane material selectivity in enhancing overall energy efficiency. Advanced membrane materials with higher selectivity for oxygen over nitrogen can achieve greater separation efficiency, thereby reducing the amount of energy needed for oxygen enrichment. This factor becomes increasingly important as industries seek more cost-effective and sustainable methods for producing oxygen-enriched air.

Technological Feasibility and Adoption: While membranes offer clear advantages in energy efficiency, the study also considered practical aspects such as scalability, reliability, and operational costs. These factors are crucial for the widespread adoption of membrane technologies in industrial applications where large-scale oxygen production is required.

Future Directions: Continued research and development in membrane materials and membrane module design are pivotal for further improving efficiency and addressing current limitations such as membrane fouling and durability under harsh operational conditions. Innovations in material science, including nano structured membranes and composite materials, hold promise for achieving higher selectivity and robust performance in oxygen-enriched air production.

In conclusion, while membranes present a compelling alternative to cryogenic distillation for oxygen enrichment, their success hinges on advancements in membrane materials and ongoing technological refinements. By leveraging high selectivity materials and optimizing process designs, membrane-based systems can potentially revolutionize the energy landscape by offering efficient, cost-effective, and sustainable solutions for oxygen-enriched air production.

Bouwmeester, H.J.M. (2003) 'Dense ceramic membranes for methane conversion', *Catalysis Today*, 82(1–4), pp. 141–150 reviews the subject of syngas production using Mixed Ionic-Electronic Conducting (MIEC) membranes has garnered significant interest over the past decade due to its promising economic and environmental advantages compared to conventional methods. Evaluations have highlighted that achieving oxygen fluxes in the range of $5\text{--}10\text{ ml cm}^{-2}\text{ min}^{-1}$ (STP), and preferably higher, is crucial to realizing the potential benefits of this technology.

Research has indicated that several membrane materials discussed in recent reviews demonstrate performance values within this desired range. These materials exhibit the necessary combination of high ionic conductivity and electronic conductivity to facilitate efficient oxygen separation and subsequent syngas production.

Furthermore, there have been successful instances of stable continuous operation reported in specific cases. This milestone is critical for demonstrating the feasibility and reliability of MIEC membranes in industrial-scale applications for syngas production.

Overall, the advancements in MIEC membrane technology underscore its potential to revolutionize syngas production processes, offering improved efficiency and reduced environmental footprint compared to traditional methods. Continued research and development in this field hold promise for further optimizing membrane materials and operational parameters, thereby paving the way towards widespread adoption of MIEC membranes in sustainable energy and chemical production industries.

Research Significance

Research into advanced materials like Gadolinium-doped Ceria (GDC) holds significant promise in the realm of energy systems, particularly for enhancing oxygen separation processes. GDC has garnered attention due to its exceptional properties such as high ionic conductivity, thermal stability, and advantageous redox properties. These attributes are pivotal for various applications including solid oxide fuel cells (SOFCs), oxygen sensors, and membrane reactors.

In the context of solid oxide fuel cells (SOFCs), GDC plays a crucial role in improving the efficiency and performance of these devices. Its high ionic conductivity facilitates rapid oxygen ion transport across the electrolyte, which is essential for achieving high power density and operational stability in SOFCs. Moreover, GDC's thermal stability ensures robust performance under the demanding operating conditions typical of fuel cell technologies.

In the realm of solid oxide fuel cells (SOFCs), Gadolinium-doped Ceria (GDC) stands out as a pivotal material for enhancing both efficiency and performance. Its role is fundamental due to a combination of exceptional properties that address key challenges in SOFC technology.

First and foremost, GDC's high ionic conductivity is instrumental in facilitating the swift transport of oxygen ions across the electrolyte of SOFCs. This conductivity is crucial as it directly impacts the cell's ability to convert chemical energy into electricity efficiently. The rapid movement of oxygen ions ensures that the electrochemical reactions necessary for power generation proceed smoothly and at high rates, thereby enabling SOFCs to achieve substantial power densities.

Furthermore, GDC exhibits robust thermal stability, which is essential for maintaining consistent performance under the demanding operating conditions typical of fuel cell applications. SOFCs operate at elevated temperatures, often exceeding 700°C, where materials must endure thermal stresses and potential degradation over time. GDC's ability to withstand these harsh conditions without significant deterioration ensures the longevity and reliability of SOFCs in practical applications.

Beyond its conductivity and thermal stability, GDC also possesses advantageous redox properties that contribute to its effectiveness in SOFCs. These properties enable GDC to maintain its structural integrity and functional properties across varying oxygen partial pressures, which is crucial for maintaining operational stability and efficiency over extended periods.

In summary, GDC plays a critical role in advancing SOFC technology by enhancing oxygen ion transport, ensuring thermal resilience, and maintaining operational stability. Its unique combination of properties makes it a cornerstone material in the quest for more efficient and sustainable energy solutions. As research continues to refine and optimize GDC and its integration into SOFC systems, the potential for broader adoption of SOFC technology in energy generation, from portable applications to grid-scale installations, continues to grow.

Beyond SOFCs, GDC is integral to the development of advanced oxygen sensors capable of precise and reliable detection in various industrial and environmental settings. Its ability to selectively conduct oxygen ions enables sensitive monitoring of oxygen partial pressures, crucial for optimizing combustion processes, environmental monitoring, and healthcare applications.

Furthermore, GDC holds promise in membrane reactor technologies where selective oxygen separation is pivotal for enhancing process efficiency and reducing environmental footprint. By leveraging its unique redox properties, GDC-based membranes enable efficient conversion and purification processes in chemical production, thus contributing to sustainable manufacturing practices.

Overall, the research into Gadolinium-doped Ceria underscores its pivotal role in advancing energy technologies towards greater efficiency and sustainability. Its exceptional combination of properties makes it a cornerstone material for future innovations in energy conversion, environmental monitoring, and industrial processes, offering tangible pathways towards a more sustainable energy future. Research into Gadolinium-doped Ceria (GDC) represents a significant stride towards advancing energy technologies with enhanced efficiency and sustainability at its core. GDC's unique properties, including high ionic conductivity, excellent thermal stability, and advantageous redox characteristics, position it as a cornerstone material for future innovations across multiple fronts.

In the realm of energy conversion, GDC plays a crucial role in improving the performance of solid oxide fuel cells (SOFCs). Its high ionic conductivity facilitates rapid oxygen ion transport through the electrolyte, enabling SOFCs to achieve higher power densities and operational stability. This capability not only enhances the overall efficiency of fuel cell systems but also contributes to reducing greenhouse gas emissions by enabling cleaner energy generation.

Moreover, GDC's thermal stability ensures reliable operation under the demanding conditions typical of energy conversion technologies, thereby extending the lifespan of fuel cells and enhancing their

reliability in diverse applications. This resilience is essential for scaling up energy solutions and integrating them into existing infrastructure seamlessly.

Beyond energy conversion, GDC holds promise for revolutionizing environmental monitoring capabilities. Its ability to selectively conduct oxygen ions makes it ideal for sensitive and precise oxygen sensing applications. This capability is crucial for optimizing combustion processes in industries, monitoring air quality, and enabling advanced healthcare diagnostics, thereby contributing to sustainable development and improving public health outcomes.

Beyond its critical role in energy conversion technologies, Gadolinium-doped Ceria (GDC) holds significant promise for revolutionizing environmental monitoring capabilities, particularly in applications requiring precise oxygen sensing.

GDC's ability to selectively conduct oxygen ions makes it exceptionally well-suited for sensitive and accurate oxygen sensing applications across various sectors. In industrial settings, precise monitoring of oxygen levels is crucial for optimizing combustion processes. By integrating GDC-based sensors, industries can achieve more efficient and cleaner combustion, leading to reduced emissions and enhanced energy utilization efficiency. This capability not only improves operational efficiencies but also contributes to environmental sustainability by minimizing pollutants released into the atmosphere.

Moreover, GDC's high sensitivity and reliability in oxygen sensing are invaluable for monitoring air quality in urban environments and industrial facilities. Real-time monitoring of oxygen levels enables prompt detection of changes in air composition, facilitating early intervention and mitigation strategies to safeguard public health and the environment. This capability is particularly critical in urban areas where air pollution poses significant health risks, enabling authorities to implement targeted measures for pollution control and public health protection.

In healthcare, GDC-based sensors offer advanced diagnostic capabilities by enabling precise measurement of oxygen levels in medical gases and biological systems. This capability is essential for monitoring patients' respiratory functions and ensuring optimal oxygen therapy delivery, thereby improving treatment outcomes and patient safety. The sensitivity and stability of GDC sensors ensure reliable performance in medical applications where accuracy and consistency are paramount.

Furthermore, GDC's potential extends to environmental monitoring beyond terrestrial applications. Its suitability for oxygen sensing in space exploration environments underscores its versatility and robustness in extreme conditions, supporting scientific research and exploration missions.

Overall, the integration of Gadolinium-doped Ceria into oxygen sensing technologies represents a significant advancement in environmental monitoring, healthcare diagnostics, and industrial process optimization. By enhancing our ability to measure and control oxygen levels with precision, GDC contributes to sustainable development goals by promoting cleaner industrial practices, improving air quality management, and advancing healthcare outcomes globally. Continued research and innovation in GDC-based sensor technologies promise further enhancements in performance and applicability, paving the way for more effective environmental stewardship and public health protection.

In industrial processes, GDC-based membranes are instrumental in membrane reactor technologies where selective oxygen separation is pivotal. By leveraging its redox properties, GDC enables efficient conversion and purification processes in chemical production, reducing energy consumption and waste generation. This not only enhances process efficiency but also aligns with global efforts towards sustainable manufacturing practices.

Overall, the ongoing research and development of Gadolinium-doped Ceria underscore its pivotal role in advancing towards a more sustainable energy future. By combining its exceptional properties with innovative applications in energy conversion, environmental monitoring, and industrial processes, GDC offers tangible pathways to mitigate environmental impact, enhance energy efficiency, and foster sustainable development globally. Embracing GDC as a key material in these sectors holds

promise for achieving cleaner, more efficient energy systems and contributing positively to global sustainability goals.

Experimental procedure

The gadolinium doped ceria (GDC) of the composition $Gd_{0.1}Ce_{0.9}O_{1.95}$ was obtained by the combination of the metal cations and the citrate from the nitrate precursors. As a precursor, cerium and gadolinium nitrate hexahydrates were used. Prior to the merge of solution each nitrate was dissolved in water individually. The dehydrated form of citric acid was dissociated in water and then was added to the cation solution. The stoichiometric ratio was coming as 1:2 between total oxide (TO) and citric acid (CA). After the solution was made uniform, the raising of temperature was done to $80^{\circ}C$ and the solution was agitated constantly to eliminate any excess water converting it into a form of transparent gel.

The precursor experienced an initial thermal decomposition at a temperature of $250^{\circ}C$ for a period of 1 hour. The resultant product, resembling ash, was then exposed to calcination at a temperature of $500^{\circ}C$ for a period of 1 hour.

To prepare the material for practical applications, the calcined GDC powder was pressed into cylindrical pellets. The pellets were formed using a steel mold with a diameter of 12 mm and a thickness ranging from 1 to 2 mm. Uniaxial pressing at a pressure of 98 MPa was employed to ensure the formation of dense and uniform pellets. The green pellets were then sintered at a high temperature of $1500^{\circ}C$ for 3 hours in an oxygen-rich atmosphere. Sintering at this elevated temperature facilitates the densification of the pellets and enhances their mechanical strength. The oxygen-rich environment was crucial to prevent the reduction of cerium ions and maintain the desired valence state of the elements. The rate of oxygen separation increases with higher permeation temperatures or increased air feed flow rates. This enhancement is attributed to accelerated kinetics or an amplified driving force for oxygen permeation.

The structural properties of the synthesized GDC powders were analyzed using X-ray diffraction (XRD). The Scherrer equation was employed to estimate the crystallite size of the calcined powders. To ensure accurate measurements, a standard-grade silicon powder was used to compensate for instrument broadening. The XRD analysis provided insights into the phase composition and crystallinity of the GDC material. The sudden change in the density may be linked to the liberation of electrons subsequent to the desorption of oxygen from the membrane material. This observation implies that maintaining high electrical conductivity is essential and likely regulates the oxygen permeation process.

The morphological characteristics of the GDC powders and sintered pellets were examined using scanning electron microscopy (SEM). SEM analysis was conducted to investigate the surface morphology, grain size, and the presence of any micro-structural defects. For the sintered pellets, SEM was also used to study the fractured surfaces, providing detailed information on the grain boundaries and porosity. To correct for air leakage through pores and/or around the membrane via Knudsen diffusion, nitrogen content was concurrently measured and utilized to calculate the net oxygen permeation. The sample was allowed to equilibrate at each temperature for approximately 45-60 minutes before recording the readings.

The density of the sintered pellets was measured using the Archimedes technique. This method involved immersing the pellets in water and measuring their buoyant force to determine their volume. The density values obtained from the Archimedes technique were used to calculate the relative density of the sintered GDC, which is a critical parameter for evaluating the material's performance in practical applications.

Results and Discussion

Powder Characterization

The structural properties of the Gadolinium-doped Ceria (GDC) were analyzed using X-ray diffraction (XRD) after the gel precursor was heated to 500°C. Figure 1 presents the XRD pattern of the calcined gel, revealing the characteristic peaks associated with GDC. All major diffraction peaks corresponding to the cubic phase of GDC were clearly observed, indicating the formation of the desired crystalline structure.

The XRD pattern displayed several prominent peaks, each corresponding to specific crystallographic planes. These summits are indicative of the GDC composition and confirm the successful synthesis of the material. The analysis of peak positions and intensities corroborated that the GDC had a fluorite-type cubic structure, a common feature of ceria-based materials doped with rare earth elements like gadolinium. This structure is particularly advantageous for oxygen ion conductivity, a key property for applications in solid oxide fuel cells and oxygen separation membranes.

The process of oxygen separation through membranes relies on the creation of an oxygen partial pressure gradient across the membrane. This gradient drives the selective permeation of oxygen molecules through the membrane material. Achieving this pressure gradient typically involves pressurizing the air feed on one side of the membrane and/or vacuuming the oxygen permeate on the other side.

Pressurizing the air feed increases the overall pressure on one side of the membrane, thereby elevating the oxygen partial pressure. This higher pressure promotes the migration of oxygen molecules through the membrane, allowing them to selectively permeate while other gases are retained.

Simultaneously, vacuuming the oxygen permeate side reduces the pressure on that side of the membrane. This lower pressure creates a favorable condition for oxygen molecules to diffuse away from the membrane and into the vacuumed space, further enhancing the oxygen partial pressure gradient and facilitating efficient oxygen separation.

By carefully manipulating pressure differentials across the membrane, engineers can optimize oxygen permeation rates and enhance the overall performance of membrane-based separation systems for various industrial applications, including gas purification, oxygen enrichment, and air separation.

One notable observation from the XRD pattern was the considerable width of the diffraction peaks. Peak broadening in XRD patterns is often indicative of small crystallite sizes. The Scherrer equation was employed to estimate the average size of the crystallites based on the full width at half maximum (FWHM) of the diffraction peaks. According to the Scherrer equation:

$$D = \frac{K\lambda}{\beta \cos \theta}$$

where D is the mean crystallite size, K is the shape factor (typically around 0.9), λ is the wavelength of the X-rays (1.5406 Å for Cu $K\alpha$ radiation), β is the FWHM of the peak, and θ is the Bragg angle. Applying this equation to the data obtained from the XRD pattern, the average crystallite size was determined to be approximately 15.39 nm.

The small crystallite size inferred from the XRD peak broadening is significant because it suggests a high degree of nanoscale dispersion of the GDC particles. This nanoscale characteristic can enhance the material's ionic conductivity, as the increased surface area and reduced grain boundary resistance facilitate the movement of oxygen ions through the material. The nanometer-scale crystallites are likely a result of the specific synthesis method employed, which involved the citrate-nitrate combustion process followed by calcination at a relatively moderate temperature of 500°C. This method helps in achieving fine and homogeneous particles, preventing the extensive grain growth that could occur at higher calcination temperatures.

1.1 Physiochemical Characterization

SEM micrographs of GDC powders made using the sol-gel method, captured at various magnifications, are shown in Figure 2. It is evident that powders are composed of plate-like monoliths

of different sizes, which are coated with smaller particles. Upon closer examination, it becomes evident that these particles are composed of polyhedral-shaped grains of roughly 3.57 μm in size. Powders are composed of small, homogeneous particles with an undefined shape. These particles are made up of grains that are roughly 3.57 μm in size and are bonded together. The morphology of grains and particles remained consistent irrespective of the gadolinium concentration in ceria, independent of the synthesis methods employed. For both preparation processes, powders with similar size of grain were analyzed.

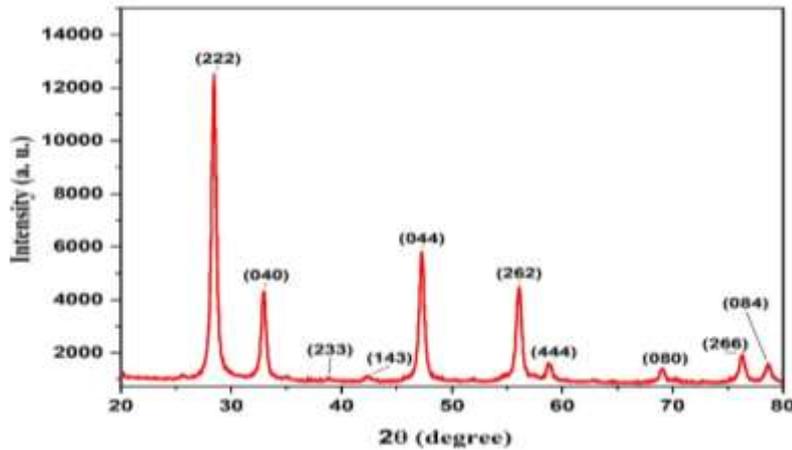


Figure 1. XRD pattern of calcined Powder $\text{Gd}_{0.1}\text{Ce}_{0.9}\text{O}_{1.95}$ at 500°C for 1 hour.

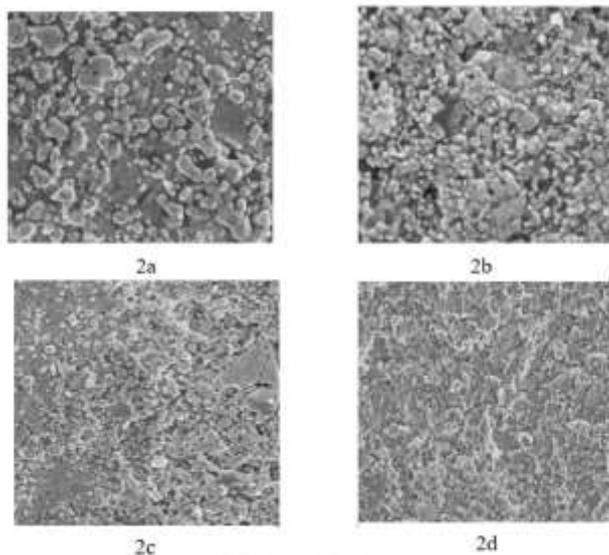


Figure 2. SEM images of calcined $\text{Gd}_{0.1}\text{Ce}_{0.9}\text{O}_{1.95}$ powder.

Optical Properties

UV-Vis diffuse reflectance spectroscopy was employed to establish the relationship between the morphology of synthesized powders and band gap energies. The reflection spectra of the GDC samples that were captured are displayed in Figure 3. It is evident that the reflection spectra of the sample which were synthesized using various methods have distinct characteristics. The powders generated from the sol-gel process demonstrate significant absorption in the spectral region of 400-600 nm, with an increase in absorption observed at shorter wavelengths. Furthermore, a correlation between the rise in Gd concentration and the decrease in absorbance was discovered. The powders generated using the combustion process exhibit a gradual drop in the intensity of reflected radiation, as the wavelength decrease from 700 to 440 nm ranging about 95% to 80%. The greatest disparity in absorbance among samples with varying synthesis methods is noted in the blue area. An abrupt increase in absorption occurs at wavelengths below around 440 nm. The values of band gap were determined by performing a linear regression analysis on the straight portion of the curve with the

highest exponential development. The optical band gap is represented by the intersection point of the curve with the energy axis. The study revealed that the band gap energies exhibit a little dependence on the chemical makeup of the powders.

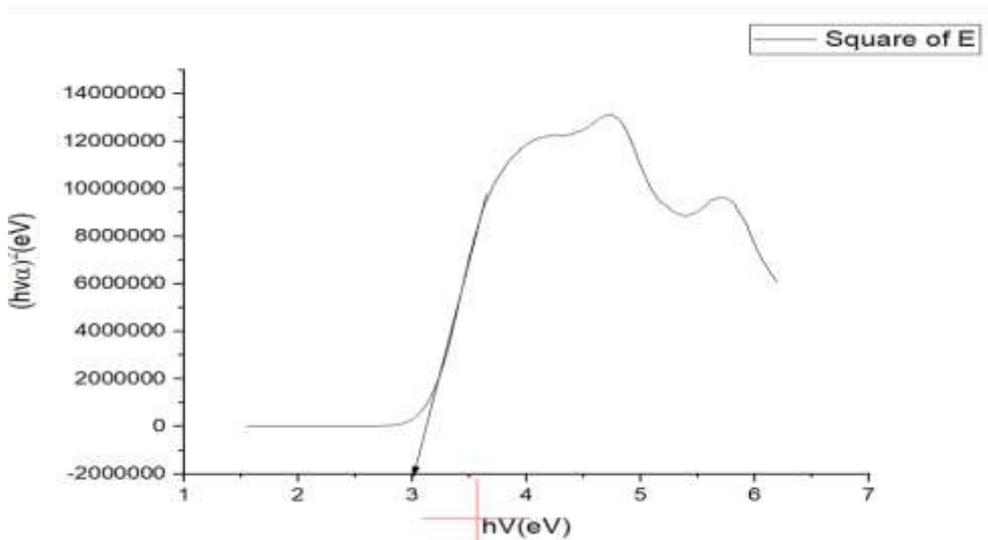


Figure 3 Reflection spectra of GDC powders obtained by sol-gel methods at 500°C

Density Analysis by X-ray photo electron spectroscopy

Solid oxide fuel cells (SOFCs) have emerged as efficient and clean energy conversion devices, with yttrium-stabilized zirconium traditionally employed as the electrolyte in classical designs [1]. However, to lower the operating temperature of SOFCs, which is critical for improving their efficiency and durability, alternative electrolyte materials with higher electrical conductivity have been sought. Among these, gadolinium-doped ceria (GDC) has shown promise [2].

GDC offers enhanced electrical properties compared to yttria-stabilized zirconia but faces challenges such as partial reduction of Ce⁴⁺ to Ce³⁺ at high temperatures and low oxygen partial pressures. Additionally, ceria-based solid solutions exhibit poor sinterability, necessitating high sintering temperatures (1400-1600°C) to achieve adequate densification (>95%). To address these issues, the use of nano-metric powder particles has been explored to improve sintering characteristics.

In recent research, the addition of cobalt (Co) and zinc (Zn) as sintering aids was investigated to enhance the processing and electrical properties of nano-crystalline GDC samples. Ceramic samples were prepared through milling, shaping, and sintering using a two-step profile with a peak temperature of 1200°C and a dwell temperature/time of 1000°C/10 hours.

Characterization of the samples was conducted using various techniques including X-ray diffraction (XRD), scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS), and impedance spectroscopy (IS). XPS analysis revealed complex Ce 3d spectra, indicating the oxidation state of cerium ions in the samples. The presence of Ce⁴⁺ was confirmed by characteristic peaks in the Ce 3d spectrum, particularly the absence of transitions indicative of Ce³⁺ in CeO₂. The Gd 4d spectrum confirmed the presence of metallic Gd, with a binding energy of approximately 140.7 eV for the Gd 4d_{5/2} peak.

Importantly, the addition of Zn or Co resulted in changes to the Ce 3d spectra, suggesting a partial reduction of Ce⁴⁺ to Ce³⁺. Impedance spectroscopy data indicated that Zn additions positively influenced sintering behavior without creating ion-blocking grain boundaries, thus improving overall material performance.

In conclusion, the study highlights the potential of GDC as an electrolyte material for SOFCs and explores the beneficial effects of Co and Zn additives in enhancing sintering properties and electrical conductivity. These findings contribute to advancing the development of more efficient and practical solid oxide fuel cell technologies.

Analysis of the Electrical Properties

The conventional equivalent electrical circuit that is formed by three sub circuits which comprises of Resistance Constant Phase Elements (R-CPE) linked in series was utilized in analyzing the impedance spectra. Three semicircles on the Nyquist plots were formed as a result in this arrangement. The semicircular pattern linked to the bulk conductivity ceases to be seen in the spectrum at temperatures over 350°C. The grain boundary semicircle ceases to exist at temperatures over 500°C. This is the outcome of the influence on the spectra of inductances formed within the experimental procedure and apparatus used. The impedance spectrum of GDC at a temperature of 250°C is shown in Figure 3, along with its corresponding fitting was done by the use of stated equivalent circuit. Instead of studying the kinetics of redox reactions at the electrodes, these circuits are used to obtain maximum precision and accurately measure of the resistance of the electrolyte. Figure 4 shows a graph representing $\ln \sigma$ Vs $1000/T$ where the activation energy can be determined by finding the slope of the line.

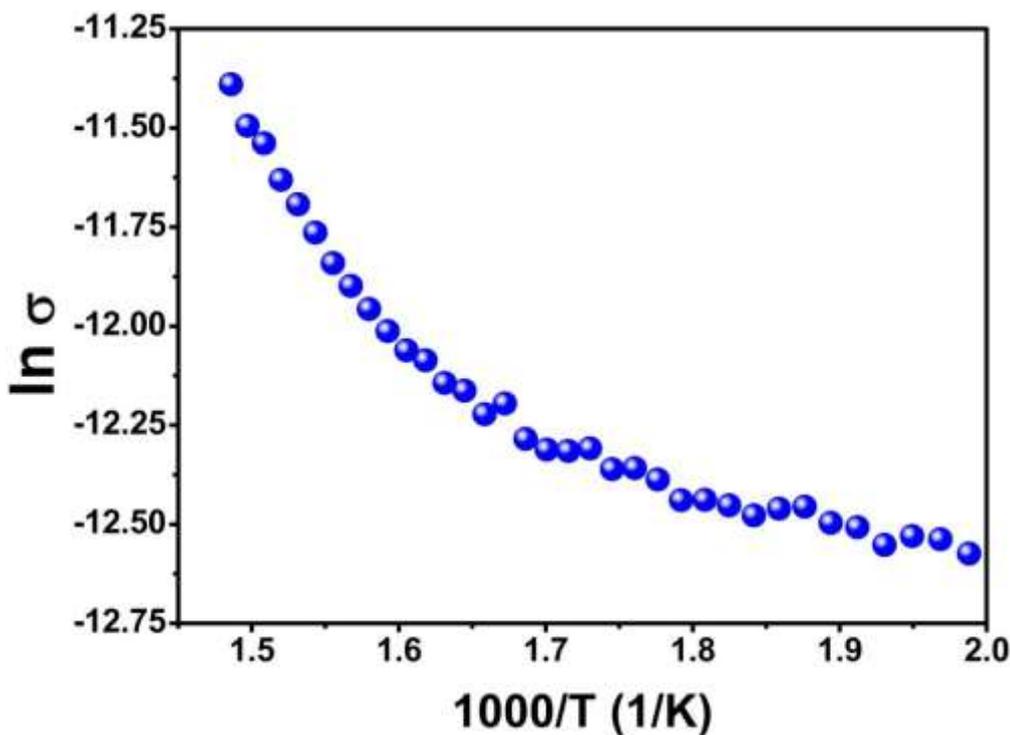


Figure 4 Graph representing $\ln \sigma$ Vs $1000/T$

For the subsequent purpose, these impedance spectra are utilized to generate Arrhenius-type plots of overall conductivity, as seen in Figure 4. Separate information is available for the identical pellets after being exposed to a temperature of 800°C for 10 h and a freshly sintered pellets (0 h). In general, the material that was subjected to sintering at a lower temperature had higher conductivity, especially when tested at lower temperatures. Moreover, the sample demonstrates a gradual decrease in conductivity over time when exposed to a temperature of 800°C. The influence is clearly observable in the sample, especially when assessed at lower temperatures. Figure 5 enhances comprehension of the issue by displaying separate Arrhenius-type graphs for bulk and grain boundary conductivity. It is worth mentioning that the sample's overall conductivity is considerably reduced in magnitude both before to and during prolonged heating. This indicates that extended heating did not cause any notable changes in the composition or phase of the overall material. However, over an extended duration at a temperature of 800°C, the overall conductivity values for the sample are slightly notable. The conductivity is 0.017 S cm^{-1} . Figure 5 represents temperature versus dielectric constant and frequency versus dielectric loss factor. Although as per the result it is believed to be the result of straight lines in different temperature ranges, indicating variations in activation energy.

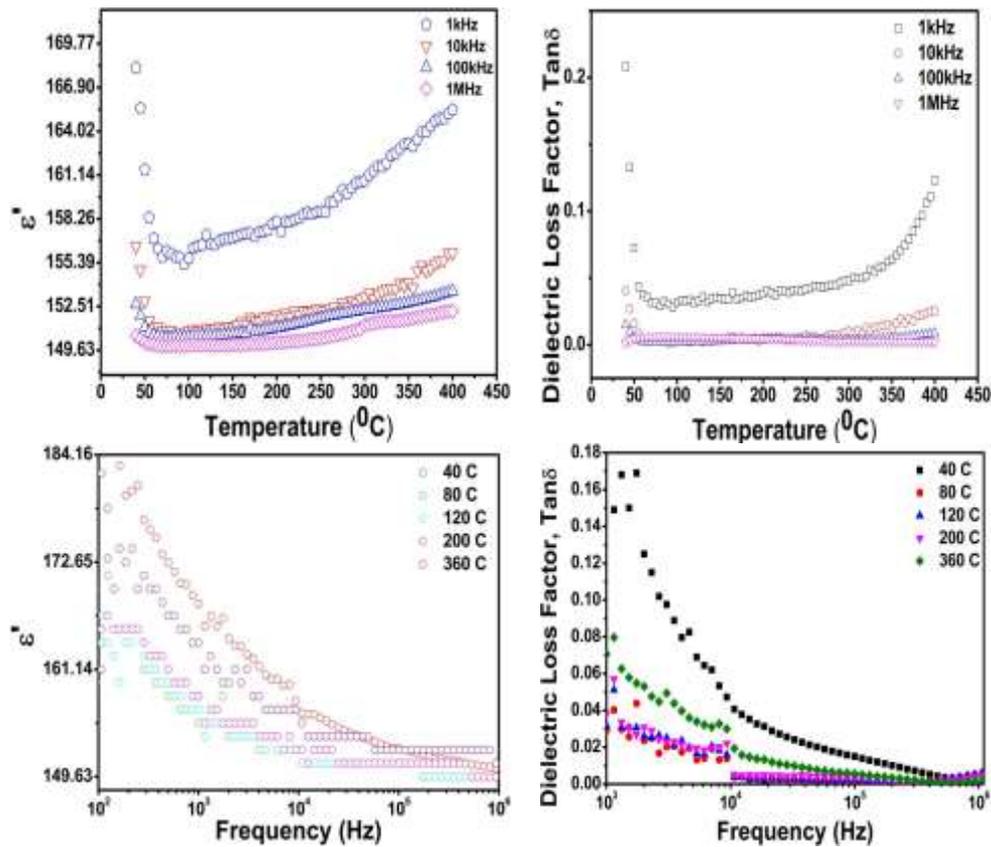


Figure 5 Graph representing temperature vs dielectric constant and frequency vs dielectric loss factor.

Utilization of Analytical method

In order to determine the utilization, the recommended analytical approach was done. Following the preparation of GDC samples exhibiting sufficiently high electrical conductivities, the oxygen flow density was further examined. Figure 5 illustrates the relationship between the oxygen flow density, $j(O_2)$, of the GDC sample and the variation in $P(O_2)$. The experiment was conducted within a temperature range of 800 to 1000 °C, with the flow of helium gas at rates of 20, 40, and 60 sccm. The plot displays a comparison of the oxygen flow ($j(O_2)$) between pure GDC covered with porous Pt, which functions as a mixed conductor, and pure GDC coated with Pt. Out of the composite materials, the one with the greatest proportion of volume ($x = 64.6$) and a membrane thickness (d) of 0.67 mm exhibited an equivalent amount of oxygen flow ($j(O_2)$) when tested at a temperature of 800 °C. To assess the practical application potential of the ceramic membranes, an analytical approach was employed. Initially, Gas Diffusion Combustion (GDC) samples were meticulously prepared to ensure they displayed sufficiently high electrical conductivities. Subsequently, the oxygen flow density was investigated.

The experimentation involved analyzing the relationship between the oxygen flow density ($j(O_2)$) of the GDC sample and variations in oxygen partial pressure ($P(O_2)$). This examination was conducted over a temperature range spanning from 800 to 1000 °C, with helium gas flowing at rates of 20, 40, and 60 standard cubic centimeters per minute (sccm).

Figure 5 illustrates the comparison of oxygen flow ($j(O_2)$) between pure GDC, coated with porous Pt serving as a mixed conductor, and pure GDC coated solely with Pt. Among the composite materials tested, the one with the highest volume proportion ($x = 64.6$) and a membrane thickness (d) of 0.67 mm demonstrated an equivalent oxygen flow ($j(O_2)$) when evaluated at a temperature of 800 °C.

This analysis provides valuable insights into the performance of the ceramic membranes under varying conditions, highlighting the influence of factors such as temperature, gas flow rate, and membrane composition on oxygen separation efficiency. Such data aids in optimizing membrane design and operational parameters for practical applications requiring oxygen separation, such as in fuel cells, gas sensors, and air separation units.

Conclusions

In this extensive study, we describe the sol-gel synthesis of Gadolinium-doped Ceria (GDC). Synchrotron radiation X-ray diffraction, UV-visible spectroscopy, scanning electron microscopy (SEM), and four-probe DC dielectric analysis were used to characterise the nanostructures.

Synchrotron radiation X-ray diffraction investigation revealed GDC nanostructure structure. After thorough investigation, the nano-structured material showed a unique cubic crystal phase, indicating outstanding structural integrity. Advanced analytical methods determined an average crystallite size of 15.39 nm, which has major implications for various applications, including surface area and catalytic capabilities.

UV-visible spectroscopy was needed to analyse GDC nanostructures' optical properties. An optical band gap width of 3.566 eV was found in the spectroscopic analysis, suggesting that the material could be useful for oxygen separation membranes and solid oxide fuel cells that require high thermal stability and low electrical conductivity.

Additionally, scanning electron microscopy (SEM) revealed GDC particle morphology. Multiple SEM images showed a complex array of morphological characteristics, with plate-like monoliths coated with smaller particles in the powders. Grain size and form homogeneity indicate sol-gel synthesis' robustness.

Dielectric investigation using the four-probe DC technique also highlighted GDC nanostructure electrical characteristics. Arrhenius-type plots were used to analyse impedance spectra to reveal overall conductivity and the material's ionic conductivity, which is crucial in electrochemical applications.

Methane (CH₄) oxidation showed encouraging results for tubular nanostructured GDC10 samples, which had higher catalytic performance than other forms. This discovery highlights the material's catalytic potential, motivating additional research in this growing sector. Modern medical devices like the portable oxygen concentrator are supported by evidence, guidelines, and intensive testing. Cost-effective and user-friendly, it addresses oxygen deficit effectively. Discs, tubes, capillaries, and hollow fibre membranes are appropriate for testing oxygen-permeable membrane (OPM) materials and optimising reaction parameters. Each setup has application-specific benefits.

Conventional pressing procedures make disc membranes convenient. Due to their simplicity, disc membranes may be quickly fabricated and scaled for screening and prototyping. The flat surface of disc membranes makes material qualities and permeation behaviour easy to characterise and analyse. The new material appears to be capable of producing oxygen from air efficiently via the thermal swing process under optimised circumstances. This shows the material's characteristics and performance have been optimised for high-temperature oxygen separation. The material's optimised temperature, pressure, and material composition suggest scalable oxygen generation applications for healthcare, industrial, and environmental cleanup.

However, tube, capillary, and hollow fibre membranes have geometry-based benefits. Gas permeation and transport are efficient in tubes and capillaries due to their high surface area-to-volume ratio. They are ideal for small designs and space-constrained applications. Hollow fibre membranes, with their porous structure and vast surface area, improve mass transfer for high-throughput applications.

Researchers can fully characterise OPM materials and optimise reaction parameters for gas separation, purification, catalysis, and sensing by combining different membrane designs. Given the large number of patented membrane modules worldwide, ceramic-based membranes with improved oxygen separation from air have excellent commercialization potential. However, numerous essential factors must be addressed to improve membrane performance. Separation efficiency and flow rates

depend on membrane shape. Maximum membrane surface area, optimum gas flow distribution, and minimum module pressure loss need optimal module design.

For gas leakage prevention and membrane system integrity, robust sealing mechanisms are needed. Researchers and producers can maximise ceramic-based membranes' potential for gas separation, purification, and oxygen enrichment by addressing these critical factors. Anisotropy can be considerably reduced when the grain size is big enough for the membrane to be a single crystal, improving oxygen permeability. When the grain size is significantly smaller than the critical value, oxygen ion transport routes become isotropic, like perovskite structures. Anisotropy can be ignored in such instances.

This extensive work describes Gadolinium-doped Ceria nanostructure fabrication and characterization. enhanced analytical methods give a complete knowledge of the material's structural, optical, and electrical properties, enabling enhanced catalysis and other applications. These intriguing results demonstrate GDC nanostructures' promise and usher in a new age of nonmaterial and catalytic innovation.

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