SOLID OXIDE FUEL CELL: AN OVERVIEW

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ABSTRACT

This paper will review the area of interest in fuel cell, especially in solid oxide fuel cell (SOFC). This area of interest covers SOFC operational reaction, its advantages and limitations, type of cell structure and configuration, and the requirement of SOFC. The review also looks into the development and fabrication of a research towards low temperature SOFC. There is also a review made by professional organizations that contribute to the research on fuel cell both locally and globally.

Keywords— SOFC, expertise

1. INTRODUCTION OF FUEL CELL

Fuel cells are the system of energy conversion devices that convert the chemical energy stored in fuel directly to electrical energy without the need of combustion process. It also produces much higher efficiency output based on the type of fuel cell and its configuration [1-2]. There are various types of fuel cells that are available, including direct methanol fuel cells, alkaline fuel cells (AFC), proton exchange membrane fuel cells (PEMFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), and solid oxide fuel cells (SOFCs) [3].

2. SOLID OXIDE FUEL CELL (SOFC)

Solid oxide fuel cells (SOFCs) are attractive because of their high energy conversion efficiency in the usage of fuels ranging from hydrogen to hydrocarbons [4-5]. A single cell configuration SOFC consists of an anode and a cathode separated by a solid oxide electrolyte (an ionic conductor) [6]. During operation, oxygen molecules are absorbed, dissociated, and reduced on the cathode surface to ionic oxygen species before incorporated into the lattice as oxygen ions. Then it moves through the electrolyte to the anode and combines with fuel molecules to form water and carbon monoxide/dioxide. Outside the cell, electrons move from the anode to the cathode through an external circuit, converting chemical energy of the fuel to electrical energy [7-8].

The advantages of SOFC are among others, has high efficiency for total power generation and good electricity generation efficiency due to its fuel flexibility and low emission. However, there is a limitation of SOFC, where it requires high operating temperature that can later cause oxidation issues.

A typical SOFC consists of the electrolyte sandwiched between the anode and the cathode, with individual cells electrically connected in series by an interconnect to create an SOFC "stack" [7-9]. There are two basic types of SOFC in terms of cell structure which are planar and tubular. Each cell structure of planar SOFC is made into a flat disk, square, or rectangular plate. For tubular SOFCs, usually the electrode (either cathode or anode) is in the shape of a long-tube with a porous wall. However, tubular SOFC is still favorable in many research and development for portable applications where rapid start-up and cool-down are required. The comparisons between planar and tubular structures are summarized in Table 1 [6].

Table 1: Different between planar and tubular cell structure

	Planar	**Tubular**
Power per unit area	Higher	Lower
Power per unit volume	Higher	Lower
Ease of fabrication	Easier	Difficult
Cost of fabrication	Higher	Lower
Ease of sealing	Difficult	Easy
Long-term stability	Fair	Excellent
Thermo-cycling stability	Fair	Good

Single cells configuration can be designed as electrolyte-supported, anode-supported, or cathode supported. The key features of each configuration are summarized in Table 2. The most popular design for SOFCs is anode-supported cell with thin electrolyte and thin cathode layer since they can be potentially operated at a lower temperature [8].

Table 2: The type of SOFC cells configuration

Cell configuration	**Advantage**	**Disadvantage**
Electrolyte supported	Strong structural support. Good gas-tightness.	Higher resistance, high operation temperature

Anode supported	Highly conductive anode. Lower operation temperature due to thin electrolyte	Potential anode reoxidation. Gas diffusion resistance due to thick anode.
Cathode supported	Lower operation temperature due to thin electrolyte	Lower conductivity. Gas diffusion limitation due to thick cathode.

SOFCs also have some of the highest gravimetric and volumetric power densities in electricity generation technology. SOFC efficiencies are size independent; making them effective for medium to large scale applications ranging from 1 Watt to multi-Megawatts. Examples of these applications include [10]:

1. 1 – 100W personal device power packs
2. 100W – 10kW uninterruptible power supplies
3. 2 – 5kW tractor trailer hotel load and/ or refrigerated trailer auxiliary power units
4. 1 – 10kW unmanned aerial, ground, and underwater vehicles
5. 1 – 15kW natural gas pipeline metering stations, radar stations, cell-phone tower power units, and infrastructure support applications
6. 100W – 100kW distributed solar energy and smart grid energy storage applications
7. 20 – 40kW automotive hybrid units
8. 60 – 90kW automotive power plants
9. 1kW – 10MW residential, commercial, and industrial applications
10. 100 – 500MW central power stations.

3. LOW TEMPERATURE SOLID OXIDE FUEL CELL

Despite many advantages, SOFCs face a major challenge in competing with other types of fuel cells because of their high operating temperature. The necessity to reduce the operational temperature of SOFCs has led to the development of research into the materials and fabrication technology of fuel cells. SOFCs normally operate at considerably high temperatures (800-1000C) to facilitate ionic charge transport and electrode kinetics [11-12]. This operation temperatures can create problems such as difficulties on construction, material and process selection, thermal expansion mismatch, lower durability and fewer opportunities to mass product [12]. In contrast, low temperature operation implies reduced operating cost, increased durability, and potential for more rapid start-up and shut-down procedures, which in turn would broaden their use as auxiliary power units for automobiles and small portable application [13-15].

Recent studies in SOFC have demonstrated its potential to operate at a relatively lower temperature (300-600 C) and with extremely high volumetric power density. [16-21]. The high power densities at low temperatures can be achieved by making the electrolyte thinner and/or developing higher conductivity materials. The past research in this field has mostly focused on developing highly ionic conducting electrolyte with compatible high performance electrodes, both cathode and anode at lower temperatures [22].

4. FABRICATION OF SOLID OXIDE FUEL CELL

Given the traditional techniques, the method to engineering pore structure is limited to manipulation of thermal fugitive particle orientation and stability during slurry preparation. The generation of graded pores is often accomplished by lamination of layers with different microstructures, however, leading to complexity and cost. There is also other researchers working towards commercialization using tape casting [23-24], screen printing [24-25], tape calendaring, extrusion [26], freeze-casting and dip processing [27-28]. All wet ceramic processing techniques discussed are a mixture of powders, pore formers, binders, and solvents that are, by multiple ways, deposited into a thin layer from single-digit to hundreds of microns thick.

Nowadays, the research towards a low temperature SOFC has led to the development of nano technique fabrication such as plasma spraying, electrostatic sprat deposition (ESD), ultrasonic mist spray pyrolysis (MSP), pulsed laser deposition, photolithography and atomic layer deposition (ALD).

Plasma spraying is a fast and well-known technique for making thin layers and coatings. It can easily produce graded structures by changing the feed material and can easily be scaled [29]. ESD atomizes a precursor solution using electrostatic forces caused by a high voltage potential. They can be collected and atomized again so little goes to waste [30-31]. MSP atomizes a precursor solution using an ultrasonic atomizer or nebulizer, and then a carrier gas transports the droplets and deposits them onto a heated substrate [32-35]. Photolithography was used to generate the micro interdigitated photoresist patterns on the substrates. PLD method was used to deposit thin films of [36]. ALD is, in principle, a layer-by-layer, surface-reaction limited thin film deposition technique relying on sterically hindered absorption of organometallic gaseous precursors that quickly diffuse on the substrate surface to form monolayers. ALD's ability to coat a conformal thin electrolyte film on non-flat or even complex geometry substrates provides a large degree of freedom in cell design [37].

5. EXPERTISE OF SOLID OXIDE FUEL CELL

In Malaysia, there are a few corporation and institutes that are established in the area of fuel cell. Table 3 shows a summary of fuel cell experts in this country.

Table 3: Expertise of Fuel Cell in Malaysia

Name	Person Contact	Description
Horizon FC Malaysia Sdn	info@horizonfuelcell.com.my	Horizon FC Malaysia Sdn Bhd

Bhd		was established with a mission to raise awareness of Malaysians towards environmentally friendly technologies.
G-Energy Technologies Sdn Bhd	info@g-energy.com.my	Focus on Research and Development, Manufacturing and Commercialization of Proton Exchange Fuel Cell Technologies and Solutions.
Advanced Materials Research Centre (AMREC), SIRIM	web@sirim.my	Priority area of medical technology flagship and covers the following areas: Biomedical Materials, Energy Materials, Engineering Materials
KGC Resources Sdn Bhd (223165-d)	sales@kgcscientific.com kgcresources88@yahoo.com	Laboratory & Scientific Equipments, Medical Instruments and Equipments
Fuel Cell Institute, Universiti Kebangsaan Malaysia	Prof. Dr. Abu Bakar Mohamad	Focus on research program, development and project demonstration to produce the technology of fuel cell
Process System Engineering of Fuel Cell Group, Fuel Cell Institute, Universiti Kebangsaan Malaysia	Prof Dr. Ir. Wan Ramli Wan Daud Prof. Dr. Jaafar Sahari Prof. Dr. Kamaruzzaman Sopian	The research projects of this group are focused on design, manufacture and control of PEM fuel cell stack.
Fuel Cell Plate Materials And Manufacture Group, Fuel Cell Institute, Universiti Kebangsaan Malaysia	Prof. Dr. Jaafar Sahari Prof. Ir. Dr. Wan Ramli Wan Daud Prof. Dr. Che Hasan Che Haron	Focus on development of plate fuel cell material and manufacture
Process Electrochemistry Fuel Cell, Fuel Cell Institute, Universiti Kebangsaan Malaysia	Prof. Dr. Abu Bakar Mohamad Prof. Dr. Abdul Amir H. Khadum Dr. Loh Kee Shyuan	Focus manufacture of electrode membrane (MEA)
Solid Oxide Fuel Cell Research Group, Fuel Cell Institute, Universiti Kebangsaan Malaysia	Prof Dr. Andanastuti Muchtar Prof Ir. Dr. Wan Ramli Wan Daud	Focuses on research aimed at developing novel electrodes and electrolytes suitable for use in low- to intermediate temperature solid oxide fuel cells.
Micro Fuel Cell Group, Fuel Cell Institute, Universiti Kebangsaan Malaysia	PM. Dr. Siti Kartom Kamarudin Prof Dr Ir Wan Ramli Prof Dr. Abdul Amir Hassan	Focussing on the development of micro direct methanol fuel cell
Advanced Membrane Technology Research Centre (AMTEC), Universiti Teknologi Malaysia (UTM)	Prof. Dr. Ahmad Fauzi Ismail	The leading research centres that has constantly engaged with its indigenous and advanced research and development of membrane technology.

Another research centre, university and corporation that led the development of SOFC in the world as in table 4 below.

Table 4: Expertise of Solid Oxide Fuel Cell in Global

Name	Description
Wachsman Group, Energy Research Center, University of Maryland	Our lab has made crucial strides in all areas of SOFC performance and operating temperature.
Computational Materials Group, Department of Materials Science and Engineering, University of Wisconsin System	Focused in catalysis for both Proton Exchange Membrane Fuels Cells (PEMFCs) and Solid Oxide Fuel Cells (SOFCs)
Scott A Barnett Research Group, Department of Materials Science and Engineering, Northwestern University	Our group focuses on energy and advanced technology applications through the investigation of solid oxide fuel cells and transparent oxide semiconducting thin films.
Energy Materials Laboratory, Korean Institute of Energy Research (KIER)	Focused on development of various cross-cutting technologies and convergence research on energy

	technologies such as AMTEC, SOFC/PEMFC, SOEC,
Centre for Hydrogen and Fuel Cell Research, University Birmingham	The Centre focuses on Research and Development, applications and demonstrations of Hydrogen and Fuel Cell systems
Materials Science and Engineering, Imperial College London	Produced a world-leading SOFC fuel cell module which provides the core component for a variety of applications and fuels.
NSERC Solid Oxide Fuel Cells Canada (SOFCC) Strategic Research Network	The Network is an association of 21 research groups from universities and government partnered with Canadian industry
UW Electrochemical Surface Science (UWESS), University of Washington	Examines surface science phenomena related to electrochemical situations, with an emphasis on fuel cells and related technologies.
International Institute for Carbon-Neutral Energy Research, Kyushu University	Develop efficient, cost-effective, and stable methods to convert hydrogen and other fuels into electricity using a fuel cell.
Nanoscale Prototyping Laboratory, Stanford School of Engineering, Stanford University	Focuses on fundamental parts: electrolyte and electrode
Meilin Liu Group, School of Materials Science & Engineering, Georgia Institute of Technology	Focus on fundamental understanding of the effect of structure, composition, morphology, and defects on electrical, chemical, catalytic, and electrochemical properties of ionic and electronic conductors.
Fuel Cell Materials and Manufacturing Laboratory, University of Toronto	Current projects are aimed at lowering the cost and improving the durability of fuel cells through the use of new materials and processing techniques to produce fuel cells more rapidly using a process that is easily scaleable.
Solid Oxide Fuel Cell Materials Design Group, Global Research Center for Environment and Energy based on Nanomaterials Science (GREEN)	Design of high quality fuel cell materials by combination of microanalysis, defect simulation and processing route design
Fuel Cell Materials, Deans' task Force on Energy Security and Sustainability, Virginia Tech	Development of solid oxide fuel cells (SOFC) for long-term operation
Department of Chemical and Materials Engineering, University of Alberta	Solid oxide fuel cells for utilization of coal, syngas, natural gas, H2S and petroleum resources with high efficiency and low impact on the environment
Fuel Cell Materials Group, National Institute of Advanced Industrial Science and Technology (AIST)	Development of materials and related characterization technologies for solid oxide fuel cells (SOFC), a high-temperature type of fuel cell
Fuel Cell Research Centre (FCRC), Queen's University	To improve performance, reliability, and durability while reducing the cost of fuel cell components and systems through innovations in materials, design, and manufacturing processes.
The Electron Microscopy for Energy and the Environment Group, Arizona State University	Current Projects, Oxygen Ion Conductors, Fuel Cell Anode and Fuel Reforming Catalysts
Central Glass and Ceramic Research Institute, Council of Scientific and Industrial Research	The major areas of research in the Division are: solid oxide fuel cell (SOFC), lithium-ion battery (LIB) and mixed ionic and electronic conductor (MIEC) based dense ceramic membrane for gas separation
Solid State Ionics and Electroceramics Research group, California Institute of Technology	The exploration of SOFC cathode materials is the focus of Moureen's research at the Resnick Sustianability Institute
Energy Research Institut, Nanyang Technological University	Focuses high temperature Solid Oxide Fuel Cells and low temperature Polymer Electrolyte Membrane Fuel Cells (PEMFC)
Research & Development, NGK Insulators, LTD	Our development efforts are directed toward such products exploiting ceramics as solid oxide fuel cells (SOFC) and large lithium ion batteries for vehicles
Multi-Functional and Energy Ceramics Group, West Virginia University	Development of piezoelectric/dielectric materials, chemical sensors, reforming catalyst, battery materials, solid-oxide and direct-carbon fuel cells, and ceramic separation membranes.
Fuel Cell and Hydrogen Research	Focus on degradation processes in fuel cell materials

Lab (FCHRL), Rensselaer Polytechnic Institute	and identify specific mechanisms through application of structure-processing-property relationships.
DTU Energy, Department of Energy Conversion and Storage, Technical University of Denmark	Develops high-performance solid oxide fuel cells (SOFCs) consisting of thin layers of advanced ceramics (and for certain types also metals)
Electrochemical Energy Technology, Institute of Engineering Thermodynamics	Development of solid oxide fuel cells (SOFC) and electrolysers (SOEC)
Department of Physics, Materials Science Group, Comsats Institute Of Information Technologly Islamabad	Focused on sub-field of Renewable Energy Resources called Fuel Cell Technology
Electrochemical Materials & Nonmetallic Inorganic Material, ETH Zurich	Focuses on both material and fundamental aspects of solid oxide fuel cells (SOFC)
Heat and Power Division of Department of Energy Technology, KTH Royal Institute of Technology	The project (TriSOFC) aims to develop and evaluate the performance of the first-of-its-kind LT-SOFC tri-generation system for low carbon buildings
Electrochemical Process Engineering, Institute of Energy and Climate Research, Julich Forschungszentrum	Work focuses on the electrochemical characterization of cells and stacks.
The FuelCell Energy Direct FuelCell (DFC)	We have incorporated the larger-scale SOFC components into fuel cell stacks as large as 60 kilowatts (kW) as part of FCE's project under the U.S. Department of Energy Solid State Energy Conversion Alliance (SECA) program
Materials and Systems Research, Inc	MSRI's facilities include over 15 high-temperature furnaces, three ovens, a surface grinder, two tape casting machines, an isostatic press, a laminating press, and six fuel cell testing systems.
Nano and Microengineering of Materials (NMAM) Group	Design of new SOFC anode materials with enhaced catalytic properties towards the direct oxidation of hydrocarbons
School of Engineering and Applied Sciences, Harvard University	Ultra-thin oxide membranes and solid oxide fuel cells
RIST (POSCO/ POSCO Energy)	Focus on Planar SOFC.
School of Materials Science and Engineering, Huazhong University of Science & Technology	Solid Oxide Fuel Cell: including SOFC design, materials, fabrication and system integration; successfully developed compressive sealing materials
The Joo Group, UNIST	LT-SOFC, electrodes. High performance cathode materials.
Professor Choi's Laboratoty for Fuel Cell Research, POSTECH	Micro-SOFC Monolith SOFC, Defect chemistry, NaS battery, Reforming. Cells for stacking (MEGA) Segmented (SEGA), Planar (PEGA) Ceramic interconnect, Reforming.
Materials Science and Engineering, Inha University	Fabrication Interconnects Cathodes. Tubular SOFC Cells and Stacks.

6. CONCLUSION

This review discusses the important role and contributions made by professional organisations that has led to the development of fuel cell especially solid oxide fuel cell operating at a lower temperature. The basic understanding of fuel cell is also important before starting the research. This paper is also shows the possibility of producing a thin layer of electrolyte for low temperature SOFC by using the latest nano technology fabrication techniques such as plasma spraying, electrostatic sprat deposition (ESD), ultrasonic mist spray pyrolysis (MSP), pulsed laser deposition, photolithography and atomic layer deposition (ALD).

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