Solid Oxide Fuel Cells (SOFC): main characteristics and analysis for their use in Southern Brazil with methane-containing gases

Nestor Cezar Heck [1], Aline Lima da Silva [2]

[1] Núcleo de Termodinâmica Computacional para a Metalurgia (NTCm)/ UFRGS (heck@ufrgs.br)
[2] Núcleo de Termodinâmica Computacional para a Metalurgia (NTCm)/ UFRGS (adasilva26@gmail.com)

Abstract

The solid oxide fuel cell (SOFC) represents a very interesting emerging technology for electric power generation because of its higher energy conversion efficiency, extremely low environmental pollution, and potential use of some renewable energy source as fuel. The present article aims at introducing the reader to an overview of the SOFC technology, showing its fundamental principles and describing how it works. Then, a more detailed analysis from technical and scientific points of view is applied to the SOFC-based power units. Finally, a critical overview of the conditions for the development of power units based on SOFC in Southern Brazil is presented.

Key words: SOFC. Biogas. Southern Brazil.

Theme Area: energy and renewable energy

Células a Combustível de Óxido Sólido (SOFC): principais características e análise para a sua utilização no sul do Brasil com gases contendo metano

Resumo

A célula a combustível de óxido sólido (SOFC) representa uma tecnologia emergente muito interessante para a geração de energia elétrica devido à sua grande eficiência de conversão, baixa poluição ambiental, e uso potencial de alguma fonte de energia renovável como combustível. O presente artigo visa introduzir o leitor à tecnologia SOFC, mostrando seu princípio fundamental e funcionamento. Em seguida, uma análise mais detalhada com critérios técnicos e científicos é aplicada às instalações de potência baseadas na tecnologia SOFC. Por fim, uma visão crítica das condições para a produção dessas unidades de potência com base em SOFC no Sul do Brasil é apresentada.

Palavras-chave: SOFC. Biogás, Região Sul.

Área Temática: energia e energia renovável.

1 Introdução

1.1 Fuel cells and the technology transfer

The perceived usefulness of any *new* technology – like that offered by *fuel cells* – does not imply in prompt adoption; frequently the lack of 'facilitating conditions' can delay the time it will become a common element of the society. Adoption of a new technology is often very costly (for various reasons) and, in a world where demand is uncertain, companies are likely to be unsure about whether or not they can recover the cost (or how long it may take to recover it). As a result, they might feel uncomfortable in adopting the technology, even if it shows a great potential for acceptance.

The whole process of adoption of a new technology over time, described originally by Beal and Bohlen in 1957, is now typically displayed as a classical 'normal distribution' (bell curve). So, the current 'technology adoption lifecycle' model describes the adoption or acceptance of a new product or innovation (*diffusion*), according to the demographic and psychological characteristics of defined adopter groups. They are: innovators (*technology enthusiasts*), early adopters (*visionaries*), early majority (*early and late pragmatists*), late majority (*conservatives*) and laggards (*skeptics*). Yet, is the *pragmatist* segment that ultimately decides on the success of a high tech solution and adopts the new technology – firstly niche-specific markets are satisfied, later the stage of mass production is achieved.

The aforementioned explanation is valid for the spreading of a new technology within a country, nevertheless the majority of the high tech products all nations consume come from few industrialized countries. So, looking *across* countries, frequently a technology adoption *lag* can be identified. Factors such as the level of economic development, natural features, or culture can play an important role in *technology transfer* and might be considered among its causes. The differences in the point of adoption of proven beneficial technologies by some country can be found *e.g.* in price: some developing societies simply cannot afford it, or do not have the same financial incentives or tax reduction policy existing at their birth place.

At present times, the adoption of *import substitution industrialization* policy by most developing countries – Brazil included – also interferes with technology transfer processes, posing them newer challenges. This policy advocates the replacement of foreign imports with domestic production, based on the premise that a country should attempt to reduce its foreign dependency through the local production of industrialized goods. Luckily, due to differences in the tax regulatory system, import substitution industrialization may end up by favoring the reduction of product price – as seen before, an important issue concerning technology *diffusion*.

Once the import substitution industrialization challenge is overcome, products bearing the new technology tend to reproduce the sequence of events (bell curve) in the originating countries. That is, they are expensive at the first moment, being therefore accessible just to the wealthy social strata, but, again, in time, once the new technology succeeds, the mass production is achieved and they turn out to be less and less expensive, becoming affordable to many other costumers.

Yet, the acquisition and absorption of foreign technologies by developing countries (*technology transfer*), and their further development (*import substitution industrialization*), are complex processes that demand significant efforts from the technology acquirers and is becoming increasingly drawn into political negotiations between industrialized and developing countries – particularly negotiations involving international agreements on trade and environment-related issues.

1.2 Work aims

Taking all these factors as background, the aim of this paper is to present the conditions for the adoption of 'auxiliary power units', APUs, based on the solid oxide fuel cell, SOFC, technology in Southern Brazil, using methane-containing gases as fuel.
In this way, at the first moment, the present work aims at introducing the reader to a scientific outline of the SOFC technology, showing its fundamental principle and describing how SOFC-based APUs work. Then, a more detailed analysis from a technical point of view is made. Finally, a critical overview of the conditions for the development of power units based on SOC in Southern Brazil is presented in the results section.

2 Overview of the SOFC technology

2.1 Scientific analysis

Principle, unitary cell, cell stack and APU

Fuel cells are electrochemical devices that convert (potential) chemical energy in fuels into electrical energy *directly*, promising power generation with high efficiency and low environmental impact [EG&G TECHNICAL SERVICES].

Concerning *fuel*, in relation to solid oxide fuel cells, SOFC, there are at least two classes of gases which can be used: (i) reducing gases rich in CH_4 (natural gas, biogas, etc.) and (ii) rich in H_2 (syngas, process gas, etc.). While the first type of fuel should be initially *reformed* with steam and / or oxygen, the H_2 rich gas may be supplied directly to the cell (the SOFC is not poisoned by CO, but the gas must be free of gaseous constituents containing S and Si). Either way, SOFC may use a very large variety of gases (or gases produced from solid and liquid fuels) as power source.

Each unitary *cell* of the *stack* (see below) consists of anode, cathode, electrolyte and interconnectors. Oxygen from the air, abundant in one side of the solid oxide membrane (cathode), receives two electrons and diffuses as O^{2-} ions through the electrolyte to react primarily with the H_2 and CO on the opposite side of the solid membrane (anode), giving as products water and CO_2 (releasing back the electrons to the electronic circuit). The electromotive force that arises between the two sides of the solid electrolyte by difference in oxygen concentration, collected by interconnects, can be harnessed by the load (motors, lights, appliances) connected to the electric circuit.

Similarly to batteries, unitary cells (repeat units) are electrically coupled together in series to form *cell stacks* with the desired output capacity; theoretically, *power* is equal to stack voltage times electric current. While stack voltage depends on the number of unitary cells connected in series, electric current – apart from kinetic-related aspects *i.e.* keeping the reaction rate as well as all transport phenomena-related issues identical – is linked directly to the electrochemical reaction interface *area*. Thus, great stack (total) area is basic for a high capacity auxiliary power unit (see below), and this leads to a specific *cell power density* concept (measured in order of mW/cm^2).

An Auxiliary Power Unit, APU, has at its heart one or more stacks plus several components for the conversion of the chemical potential energy into electrical energy and can be seen as a battery that needs no charging, but fuel.

SOFC-based technology as a scientific research subject

The technology of solid oxide fuel cells is still a 'work in progress'. Yet, scientific researchers identify it as an outstanding example for a *multi-scale* system.

As stated by DLR (German Aerospace Center) in relation to the SOFC technology, *six*

levels of investigation can be recognized, which can be linked to both *time* and *dimension* scales. Mass, charge and heat transport occurs on a scale of microns over millimeters to tens of centimeters. On the other hand, time scale varies from sub-nanosecond (electrochemical and chemical reactions) over seconds (transport) up to days or even months (structural and functional degradation). In addition, all processes are strongly coupled to each other and are often not linear over the scales. Also, chemical and electrochemical reactions taking place on the nanometer scale strongly correlate with *nano* and *micro* structural properties. Consequently, processes at the micro scale can dominate the macroscopic behavior. For this reason, a detailed understanding of the relevant processes at all scales is a precondition for a computer-based optimization of fuel cell design, performance and longevity.
The six aforesaid investigation scales are [DLR]:

I - *Molecular and phase interface scale* [10^{-10} m, 10^{-9} s]
Chemical topics that are important at this level are: surface chemistry, charge transfer and double layer; main transport subject is restricted to space charge process.

II - *Surface scale* [10^{-8} m, 10^{-6} s]
A detailed understanding of competing reaction pathways, rate-limiting steps, coupling of chemical reactions with microstructural properties and the origin of degradation processes can be investigated at this research level.

III - *Electrode scale* [10^{-4} m, 10^{-2} s] (porous multi-phase mass and charge transport)
Electrodes can be seen as a porous multi-phase region where mass and charge transport take place. Therefore, transport processes in porous layers with the search for effective parameters for the *continuum* models, for example, effective surfaces and phase boundaries, transport coefficients, relative permeability, etc. are important research subjects.

IV - *Cell scale* [10^{-2} m, 10^{0} s] (mass, charge and heat transport)
At this level, mass, charge and heat transport are important subjects. However, it must be kept in mind that transport behavior at the cell level is linked to detailed models of the surface and electrode plane as well as to higher dimension scale. Geometry is very important at this investigation level, however, due to the high computation time, normally only a simplified description of the transport processes can be implemented.

V - *Stack scale* [10^{-1} m, 10^{2} s] (mass, charge and heat transport)
Besides the differences on the dimension and time scale, the same statements given at the cell level are valid here.

VI - *System scale* [10^{0} m, 10^{4} s] (process simulation)
At the system level, focus is on understanding, optimizing and controlling of the interactions between fuel cell stack and peripheral components. Important subjects are: prediction of dynamic load behavior, evaluation and optimization of system efficiency, component selection and optimal system design, and the development of control strategies.

A *seventh* level of investigation could be added to the original six already mentioned, which is related to the *electrical grid*.

Due to the increasingly contribution of 'small scale electrical generation' (*e.g*. PV, wind, solar, *fuel cells*, microturbines, etc.) located at or near customer sites, often interconnected to the utility for reliability and power back up, the term Distributed Generation (DG) came into sight in opposition to Bulk Generation, BG, that is electricity generation from renewable and non-renewable energy sources in *bulk* quantities distributed by the grid. To make this scheme clearer, the term *smart grid* was created to describe the electrical power system that is characterized by the increased use of communications and information technology in the generation, delivery and consumption of electrical energy (the term smart grid does not distinguish between BG and DG; in the USA, the *Smart Grid Conceptual Model* from the National Institute of Standards and Technology, NIST, defines seven important domains: Bulk Generation, Transmission, Distribution, Customers, Operations, Markets and Service Providers; DG concept is mainly located inside the Customer domain of the smart grid [IEEE]).

Of concern to this work is the fact that *integration* of all these systems raises new *operational* worries. Consequently, in order to investigate the stability and dynamic behavior of the utility distribution (macro and micro) grid with small system inertia and power quality interactions in inverter based DG, some research projects are currently being undertaken on this subject in the industrialized countries (RPI, FZ-JUELICH, SEE), as well as in Brazil – this can be seen *e.g.* in the recent research funding raised by the National Council of Technological and Scientific Development entitled 'Smart Grids Technology' (MCTI / CNPq / CT – ENERG Nº 33/2013).

Time and space scales in this seventh investigation level are in their highest level.

2.2 Technical analysis

The auxiliary power unit, APU

APU systems based on SOFC technology carry the characteristic of the fuel cell 'family' *i.e.* they are electric generators with little 'moving parts'. However, they are far more simpler than similar units based on Proton Exchange Membrane Fuel Cell, PEMFC, technology (highly complex because of the large number of reactors involved, which consume part of the energy generated, reducing the overall process efficiency), and, at a proper scale, more efficient than electromechanical power generators powered by diesel engines.

The capacity of the auxiliary power unit is a multiple of that of the cell *stack*, consequently it has all the advantages (and disadvantages) of module-based technologies.

Basically, in addition to the *cell stacks*, an SOFC-APU consists of many *components*: reformer, burner, heat exchangers plus the components responsible for the cleaning of the gas; these components, interconnected by gas piping, constitute what is called the 'balance-of-plant', BoP.

References to *high* and *low temperature* sections of the gas piping can be made here. To cope with frequent problems such as high temperature oxidation, chromium volatilization in high temperature section of the piping (including heat exchangers, etc.), ferritic stainless steels, nickel (also used for brazing) or other more exotic Ni-Co-base superalloys materials are required; another approach is to use zirconia and aluminide coatings for internal *lining*. Materials used in parts under low temperature can be ordinary materials, because they are not so subject to those harsh conditions.

Main part of the heat from the electrochemical reactions (plus heat stemming from the burning of the unused fraction of cell gases) is reinserted into the system by means of heat exchangers; excess heat can be used in ancillary facilities (*e.g.* the anaerobic digester) or for central heating purposes. When (besides electricity) only *heat* is generated, the unit is of the type 'combined heat and power', CHP, when generation also includes the production of *cold*, the power unit becomes 'combined cold, heat and power', CCHP.

The electromotive force generated by any fuel cell is of the DC type, so an inverter is needed in order to convert the electricity into AC – the type most widely used in general electric equipment.

For safety and reliability reasons, the system must work autogenously – *i.e.* it generates the electricity it consumes. Working independently, it will not be affected by unexpected power supply interruptions in the grid.

About the APU structure

Similarly to a living organism, *three* independent networks can be identified in the APU connecting several base *components*:

I - *Matter* (gas piping)
Gas handling components (compressors / blowers, ejectors, shut-off valves, flow control valves); gas conditioning components (filters / soot traps, desulfurizer, desiliconizer, other gas absorber chemicals for NH_3 and halogens); chemical conversion components (reformer, cell stack, afterburner) and gas heat transfer components (heat exchangers).

II – *Power* (electronic conductors)
DC/AC Inverter.

III – *Information* (data bus).
Programmable controller (PLC); sensors and actuators.

While power and information circuits conduct electricity, matter circuit conveys the gas phase.

In *gaseous matter circuit* energy contained in chemical bonds is converted into electricity but part leaves it as heat (most of the heat must be reinserted into the gas circuit; the remaining fraction may be used by ancillary facilities).

Power circuit connects the *load* to the fuel cell (and, eventually, to the grid).

The process of conversion of energy – arriving as chemical potential energy and leaving the APU as electrical energy – is overseen by a programmable logic controller. The *information circuit* enables the PLC to take reasonable actions during operation while accompanying the signals from the system as a guide in this task. The PLC acts on valves and reads the resulting effects on sensors; the last signals provide the necessary feedback so that it can keep the system running in a perfect pitch.

3 Methodology

In the present work, a deep evaluation of the SOFC technology is carried out. After the display of the relevant information, a critical analysis is made and is presented in the *results* section. Aim is to provide a straightforward outlook about the possibilities and challenges for the production of SOFC-based APUs in Southern Brazil.

A huge amount of data related to SOFC technology is available in the published form as papers or books; nevertheless a stunning amount of information can be withdrawn from the Internet and fliers, and another great quantity of information comes from discussions conducted in technical and scientific meetings. Thus, the methodology used in this paper seeks to bring together the knowledge contained in the ‘official scientific literature’ with the more ‘freely’ spread information from websites, presentations, brochures, leaflets, discussions, etc.

In summary, sources of information can be classified, in a simple way, in three major fields:

- Fundamental (scientific); arises mainly from the analysis of scientific literature (books, articles, theses and dissertations). Its characteristic are: consolidated, general or specialized, easily available (sometimes under payment) and referenceable.

- Scientific-technical information (Internet pages, manuals, flyers, etc.); it comes from sources of assorted nature and may have some degree of volatility (as is the case, for example, with the Internet). It relates several topics, is strongly associated with scientific organizations, and may have commercial connotations; is equally very important for this study. Keywords are: focused in some product or process, volatile, not easily referenceable.
- Analytical considerations of more academic nature, stemming mainly from discussions in the internal (lectures, dissertations, theses, etc.) as well as in the external (seminars, conferences and other type of events) environments; information is mainly exchanged vocally among scientists and technical staff, and is not always previously condensed in scientific or technical books and papers. Characteristics: personal, reflects experience, from the discussion, not published, not referenceable.

All these sources are taken into consideration when condensing the results.

4 Results

Results of a rational analysis on the technology transfer under the premise of import substitution industrialization policy of APUs based on SOFC technology are displayed below. For a better understanding they are divided into several items covering most of the relevant topics related to the theme.

Fuels

The most commonly used fuel in SOFCs is the NG, however Southern Brazil lacks this type of natural energy resource. To supply it, a daily amount of about $30x10^6$ m^3 is carried by the southern section of the natural gas pipeline Bolivia-Brazil (Gasbol), operated by TGB company – Gaspetro owned, a subsidiary of Petrobras.

The pipeline, which runs over 1165 km along the coast, with origin in Paulínia (SP) and ending in Canoas (RS), has 20 city-gates located primarily in metropolitan areas of the three capitals of this region [PRATES, PIEROBON *et.al.*, TGB, EPE].

Unfortunately, as can be seen from reports in the press, the pipeline works at its capacity limit. To encourage the arrival of new industries (with a gas demand estimated at 10 million cubic meters in excess of the amount that is offered today), government plans to expand the fuel supply by (i) increasing locally the gas network in the three States, and (ii) importing gas in its liquid form (LNG). Liquefied natural gas would be carried by ships to ground stations where it would be regasified and injected into the expanded gas pipeline net [REDEPETROBRASIL, VALOR].

With the beginning of the exploitation of the so-called *Pre-salt* reservoir (oil at a great depth under the sea), it is hoped that the Brazilian NG production will be significantly increased. It was announced, however, that much of this production will be reinjected in the reservoir, in order to increase oil productivity. Only after the completion of further studies, which are currently underway, will it be possible to know how much gas will remain available to supply the Brazilian market and for how long time [MME].

Therefore, in spite of being available only to the metropolitan areas of the industrialized east coast, and without the planned expansion of the NG supply at the time being, the introduction of SOFC could still succeed at least to many *premium users* (hospitals, hotels, shopping malls), which already use natural gas to meet their needs (case of electricity generating equipment substitution).

Apart from NG, the choice of commercially available fuels suitable for application in SOFC-technology is very limited in Southern Brazil. Next to NG are biomass gasification and biogas.

Concerning biomass gasification, the greatest potential is associated with sugar cane plantation – poorly suited to Southern Brazilian climate – and 'energy forests'. On the other hand, biogas can be associated with farming and food industry waste. Farming activity is intensive in Southern Brazil. In 2011, there were 212.80 million head of cattle in Brazil, with the greatest concentration located in the South region (13.10%); there were 1.27 billion of chickens, with 46.1% located in South region (2011), while there were 39.31 million head of pigs, with 48.6% located in Southern Brazil (2010) [IBGE, 2011].

Biogas generated from domestic wastewaters could also be used for electricity production. This theme, however, is undeveloped in Brazil, even in the South region.

Biogas stands as a viable, durable, renewable energy source for the SOFC-based power units; and electricity is already being produced from biogas in many places. What is more, anaerobic digesters are much simpler and of easier operation in comparison with gasifiers.

Balance of plant (BoP)

Assuming that transfer of technology will occur under *import substitution industrialization* policy, the balance-of-plant components are those that more easily candidate to be produced locally. Balance-of-plant components like heat exchangers, reformer, etc. have complex projects – since they must face heavy duty under very demanding conditions. Nevertheless, to fabricate them industry will face a difficult but not impossible task, for the automotive industry in Southern Brazil is well developed and processes used to produce mechanical parts are to some extent similar to those used in the production of BoP components.

Inverter

The case of the inverter is quite different and more promissory. The local industry – because of other demands – is in development and able to provide these items for powers up to 50 kW.

Stack

Stack has to be entirely imported; in this respect it will not differ to what already happens with the Solar PV (solar photovoltaic) production of electricity in the country.

With exceptions, research in Brazil is located mainly in levels III and IV, previously described. Research is focused on the study of materials used in the cell (including production methods, measurement of fundamental electrochemical properties, etc.), so that there is still a large gap to the point of producing a stack locally with the required durability and stability.

System control

Programmable Logic Controllers are easily available in the Brazilian market – although they are not always manufactured in Brazil. The question of the production of software able to control the process, especially in its dynamic aspects – including therein the safe start up and shut down – is more complex task. A compromise solution would include a transition between import and development of this capacity locally.

Electric energy

The price of electricity is not cheap in Brazil, regardless of the fact that its source is largely hydro generation. This factor is *positive* when it comes to the issue of return on investment in SOFC-based APUs, as it increases the revenues obtained from the suppression of expenditure on electricity. On the other hand, most subjective issues may also contribute in the decision of adoption of this technology, for example, uninterrupted power supply for the enterprise – an component not always taken into account when considering pure monetary items.

Prospective market

How strong the demand for this technology is, is a question difficult to handle. See *fuels*, above for some considerations.

Durability issues

It is difficult to design components that can survive for decades in harsh conditions, especially the components subject to high temperatures and those that take the electricity out of the cell.

As stated by IEA [IEA], SOFC systems offer average lifetimes of some 6,000-8,000 hours (one year ~ 8,700 hours), with best results attaining 20,000 hours. However, the target lifetimes for *stationary* solid oxide fuel cell based systems are 40,000-60,000 hours. Thus, to plan preventively a restacking of the fuel cell in a period of some few years would be a conscientious attitude – certainly with reflections on the economic evaluation of the investment.

5 Conclusions

In spite of the proven benefits, Auxiliary Power Units, APUs, based on the SOFC technology are not yet produced in Brazil, due to practical, scientific and economic issues.

Nevertheless, similarly to the cases of advanced microprocessors for computers, and of photovoltaic panels, it would be perfectly possible to take advantage of this technology in Brazil by a combination of the more sophisticated imported components with locally produced components, which carry lower technology and are easier to fabricate.

By this way, the efficient use of SOFC technology will not depend on local production, but rather on the *expertise* of the workforce – including engineers of different areas (some of them are closely related to combustion, materials, process or electricity) and professionals from other disciplines, (including some from very distant fields). All these professionals should cooperate in one or another manner for the successful transfer of the technology under the *import substitution industrialization* policy.

This expertise may be achieved, for example, with more research focusing on the 'system', rather than in the ceramic materials that constitute the cells – as is done currently.

Nevertheless, in order so that the productive sector can consider this new technology in its *portfolio*, it will be necessary a clear demonstration of the benefits and reliability. This may be possible *e.g.* through a good 'merchant', such as a *demonstration* or *pilot plant* implemented locally.

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