archives
of thermodynamics
Vol. **35**(2014), No. 1, 17–41
DOI: 10.2478/aoter-2014-0002

Recent key technical barriers in solid oxide fuel cell technology

JAROSŁAW MILEWSKI[1*]
WOJCIECH BUDZIANOWSKI[2]

1 Institute of Heat Engineering, Warsaw University of Technology, Nowowiejska 21/25, 00-665 Warsaw, Poland

2 Wrocław University of Technology, 27 Wybrzeże Wyspiańskiego Street, 50-370 Wrocław, Poland

Abstract High-temperature solid oxide fuel cells (SOFCs) are considered as suitable components of future large-scale clean and efficient power generation systems. However, at its current stage of development some technical barriers exists which limit SOFC's potential for rapid large-scale deployment. The present article aims at providing solutions to key technical barriers in SOFC technology. The focus is on the solutions addressing thermal resistance, fuel reforming, energy conversion efficiency, materials, design, and fuel utilisation issues.

Keywords: SOFC; Power plant; Deployment; Technical barrier

1 Introduction

Power generation and the related environmental impacts have become important issues across the world. Electricity is becoming increasingly important form of energy. A significant increase of electricity demands is expected worldwide until at least 2050. This is mainly due to the factors such as:

- a shift of passenger and freight transport to rail,
- a gradual shift from fuel-firing to electricity in road transport,

*Corresponding Author. E-mail: milewski@itc.pw.pl

- an increase in heat pumps usage,
- predicted 4 fold in the world and 10 fold in China and India economic growths in the period 2006–2050.

Today, power is provided mainly by conventional power generation technologies that rely upon fossil fuel combustion, which generate soot and sulphur compounds, in addition to other noxious emissions as well as CO_2 [1]. Thus current power generators contribute to both local air pollution and global warming. Therefore, advanced clean energy systems must be developed urgently, allowing for making the shift from a fossil fuel-based economy to a new clean-energy-based economy in a progressive manner [2–4].

Solid oxide fuel cells (SOFCs) are an emerging alternative to traditional power generation systems. They display a multifuel capability (hydrogen, carbon monoxide, methane, syngas [5], renewable biogas [1, 6], etc.), may play a role in carbon sequestration strategies [7], and may render the highest electricity generation efficiency in power station design if combined with a gas turbine [8]. SOFCs and MCFCs (molten carbonate fuel cells) [9] offer the potential for higher power efficiencies and lower emissions.

The electrolyte of a SOFC consists of a solid, fully dense oxide metal (typically yttria (Y_2O_3) stabilised zirconia (ZrO_2) or YSZ). The anode of a SOFC is typically made of a nickel cermet, such as Ni-YSZ, while the cathode is made of strontium (Sr) doped with lanthanum manganite ($LaMnO_3$). The fact that all the components in a SOFC are solid structures makes it possible for the cells to be constructed in any geometry. The SOFC operates in the range 600–1000 °C, which allows it to be combined with other conventional thermal cycles such as gas turbine (GT) or integrated gassified combined cycle (IGCC) to yield improved thermal efficiency [7]. The hybrid SOFC system is considered to be a key technology in achieving the goals of satisfactory fuel-to-electricity efficiencies [10–14], such as 60–80% (LHV – lower heating value).

The superiority of SOFC-based systems arise from several technical features. First, they have no moving components, thus noise and vibrations associated with mechanical motion during operation are practically nonexistent. This makes it possible to install the system in urban or suburban areas as a distributed power generation plant [15]. Without moving parts, we would expect enhanced reliability and lower maintenance cost. Secondly, SOFCs (by virtue of high temperature operation) can extract hydrogen from a variety of fuels [16, 17]. SOFC is the most sulfur-resistant (as H_2S and COS) fuel cell. It can tolerate sulfur-containing compounds at concentrations higher than other types of fuel cells. In addition, it is not poisoned by carbon monoxide (CO); in fact, CO can be used as a fuel. These features allow SOFCs to be fed with gases derived from either solid or liquid fuels. This advantage is beneficial for coal-based central power generation and in vehicles that are powered by diesel or gasoline fuel. Thirdly, the size of a SOFC module is flexible, thus allowing it to be constructed for use in any power range – from watts to megawatts. Therefore, a SOFC or its hybrid system may be built for stationary applications both as central power generation and as distributed power generation.

SOFC is still an emerging power generation technology. Its potentials for large-scale power generation applications are strongly linked with technological advancements. Key technical barriers encountered in the construction and exploitation of SOFCs include insufficient thermal resistance, complexity arising from the need for reforming of hydrocarbon fuels, insufficient overall energy efficiency of SOFC stacks, and insufficient utilisation of the fuel in the anode. Solutions to those technical barriers must be found in order to achieve technological maturity and cost reduction of SOFC technology. Main achievements that address those four key technical barriers are expounded in this paper.

Table 1. Overview of energy conversion efficiencies in different systems

System	Energy Conversion Efficiency (electricity only)
Combustion engine	10–50%
Gas turbine	up to 40%
Gas turbine plus steam turbine (combined cycle)	up to 60%
Fuel cell	up to 80% (limited by technical barriers)

Energy conversion efficiency is one of the main characteristic parameters of all power generators. Energy conversion efficiency is the ratio between the useful output of an energy conversion machine and the input, in energy terms. For fuel cells, the useful output constitutes the generated electric power and the input is the usable energy content of fuel used (i.e., its usable chemical energy). Table 1 provides some examples of energy conversion efficiencies in some energy conversion related cases. It is seen that fuel cells can theoretically achieve 80% energy conversion efficiency. However, this theoretical goal requires further development of SOFC technology. Moreover, the manufacture of SOFCs is expensive and thus SOFCs still can generate electricity at relatively high costs.

Entropy minimisation is a useful design procedure for SOFCs. Sciacovelli and Verda [18] have shown that by modification of the geometrical parameters of the SOFC the overall entropy generation can be minimised and thus the efficiency can be raised. Kjelstrup *et al.* [19] have described an interesting consistent approach to energy- and material-efficient design of fuel cells. Their work has demonstrated a method to design optimal catalytic layers and gas supply systems in fuel cells, inspired by the geometry of the lung and the hypothesis for the state of minimum entropy production of irreversible thermodynamics. Some of achievements of this theoretical work are applicable to SOFC technology. Moreover, since Sciacovelli and Verda [20] have indicated that the main contributions to irreversibilities are due to mass transfer and the coupling between mass and heat transfer, thus the entropy generation reduction can be obtained by homogenisation of temperatures and concentrations in SOFC domains.

SOFCs can be used as combined heat and power (CHP) generators. For instance, the heat released during fuel oxidation can be captured and used to heat water in a microcombined heat and power (μ-CHP) application [21]. Such CHP units can achieve overall thermal efficiency as high as 80–90% at the unit. SOFC-based CHP units are being developed today for the European home market.

2 Working principles of solid oxide fuel cell

Solid oxide fuel cells allow for the conversion of chemical energy of fuel directly into electricity in the process of electrochemical reactions, and therefore without the need for high-temperature combustion of fuel as it is in classical thermo-mechanical power plants. Consequently SOFCs can overcome the Carnot cycle efficiency limitations. A simplified thermodynamic path in energy conversion is thus promising for high fuel-to-electricity efficiencies. However, existing technical barriers must be first overcome in order to enable SOFC technology to achieve technological maturity for large-scale power generation.

The SOFC operates at elevated temperature such as 600–1000 °C, in order to achieve adequate conductivity and generate enough voltage. Working principles of SOFCs are based on oxygen pressure differential between the cathode and anode sides, Fig. 1. A cathode side can be supplied by air (oxygen content of about 21%), while the anode side, in order to obtain oxygen at very low pressure, is supplied by fuel, which utilises the negatively

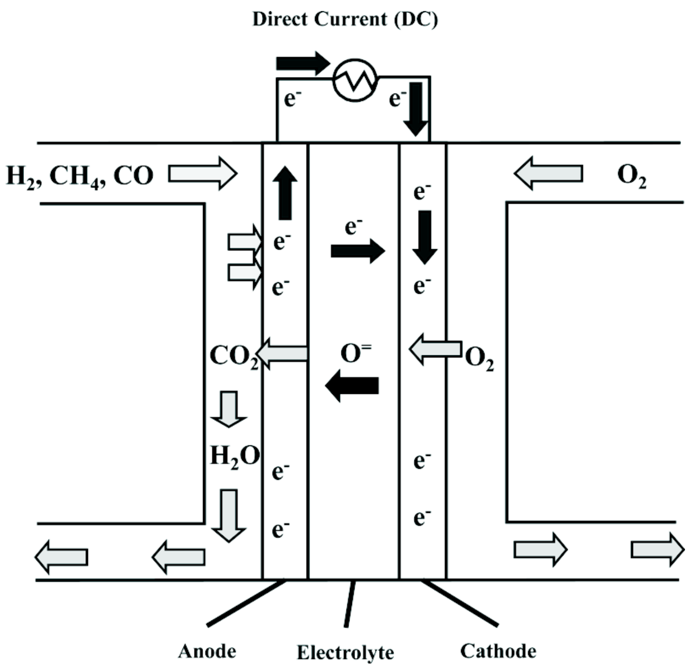

Figure 1. Working principles of a SOFC.

charged oxygen ions transferred from the cathode through the electrolyte to the anode. The excess electrons from negatively charged oxygen ions are routed back to the cathode side of the SOFC through an electrical circuit completed between anode and cathode electrodes, resulting in an electrical current flow through the circuit. Oxidation of fuel can achieve the level of oxygen pressure on the anode side of 10^{-16} Pa, resulting in a single cell voltage of 1 V. In order to obtain higher voltages, the individual cells (up to several hundred cells) are connected together in series what composes a fuel cell stack. The reverse operation is also possible [22].

Electrolyte material plays crucial role in SOFC's working characteristics. Electrolyte material determines the side of a fuel cell on which main reactions occur and where reaction products are escaped, i.e., on anode or cathode. For each type of a fuel cell, higher conductivity of the electrolyte means better performance [23]. Main material used for the electrolyte is zirconium oxide stabilised with yttrium oxide – yttria-stabilised-zirconia (YSZ). Recently, research efforts are dedicated to the development of ceria-gadolinia based electrolytes which can operate at considerably lower temperatures

(500–600 °C). The anode is made as porous cermet from nickel oxide and zirconia – NiO/YSZ. The cathode is usually made from lanthanum manganite doped with strontium – La/Sr/MnO3 (LSM). A separate bipolar plate is made from doped lanthanum chromite or metallic plates.

Mathematical modeling [24–28] is now the basic method which makes it possible to analyze systems including fuel cells. It is mainly associated with fairly expensive process of producing cells and high cost of materials used.

3 Recent key technical barriers in solid oxide fuel cell technology

Key technical barriers encountered in the construction and exploitation of SOFCs include:

(i) insufficient thermal resistance,

(ii) complexity arising from the need for reforming of hydrocarbon fuels,

(iii) insufficient overall energy efficiency of SOFC stacks,

(iv) insufficient utilisation of the fuel in the anode.

In recent years these problems have been addressed in a large number of solutions proposed. The most interesting measures that address those four SOFC's technical barriers are briefly presented, discussed and summarised.

3.1 Thermal management

In order to prevent thermal cracking, the tubular SOFC approach (made from tubes) is better than the competing planar SOFC approach (made from flat plates) because the tube is essentially one-dimensional. The tube that is heated in its middle expands but does not crack. In contrast, a ceramic plate heated in its center only would quickly break into pieces because the center expands while the outside remains the same size.

Solid electrolyte gives opportunity to construct various shapes of the cells. Currently, two solutions are the most popular, i.e., planar and tubular. Both designs have numerous advantages as well as disadvantages. Now, it seems to be difficult to indicate the most preferred design. The tubular design is used only by one manufacturer (Siemens), whereas the planar design is more widely used both in lab-scale and in commercial applications.

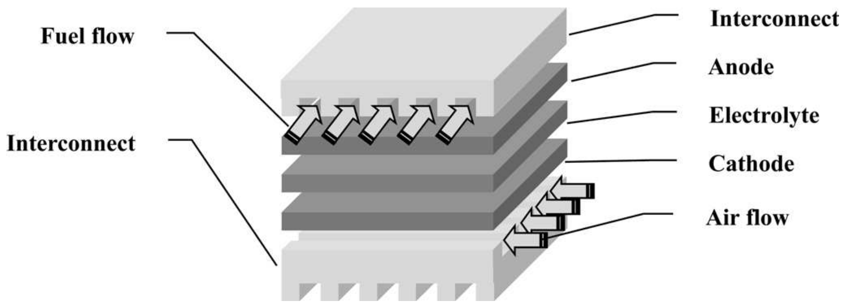

Figure 2. The configuration of a SOFC in planar design.

The concept of planar design is shown in Fig. 2.

A singular cell generates very low voltage of around 0.7 V under load, thus the cells are connected in series, what makes a fuel cell stack with more practical level of voltage (several hundreds volts). There are two approaches to construct the fuel cell stack:

- monopolar design and
- bipolar design.

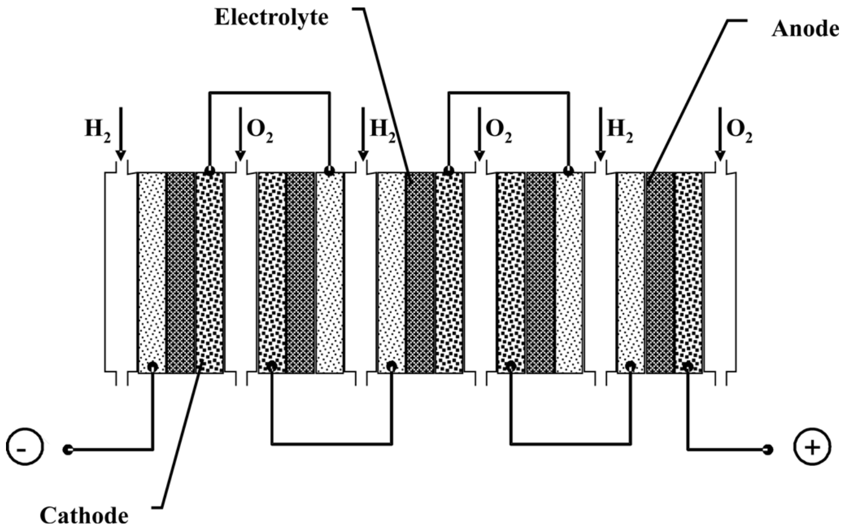

Figure 3. The monopolar SOFC of planar design.

Theoretically, monopolar design does not require any interconnector (see Fig. 3), but practically both electrodes of the same polarisation must be separated from each other to enable the gas flow. In this case the connector has no specific requirements. Often, the anode and cathode structures are implemented in specific channels by themselves. In this case the interconnector can be eliminated. Additionally, the electrodes of opposite polarisations (i.e., anode and cathode) must be connected to each other by wires, mounted outside of the stack. This complicates the total stack construction and is a reason that monopolar configuration is used very rarely.

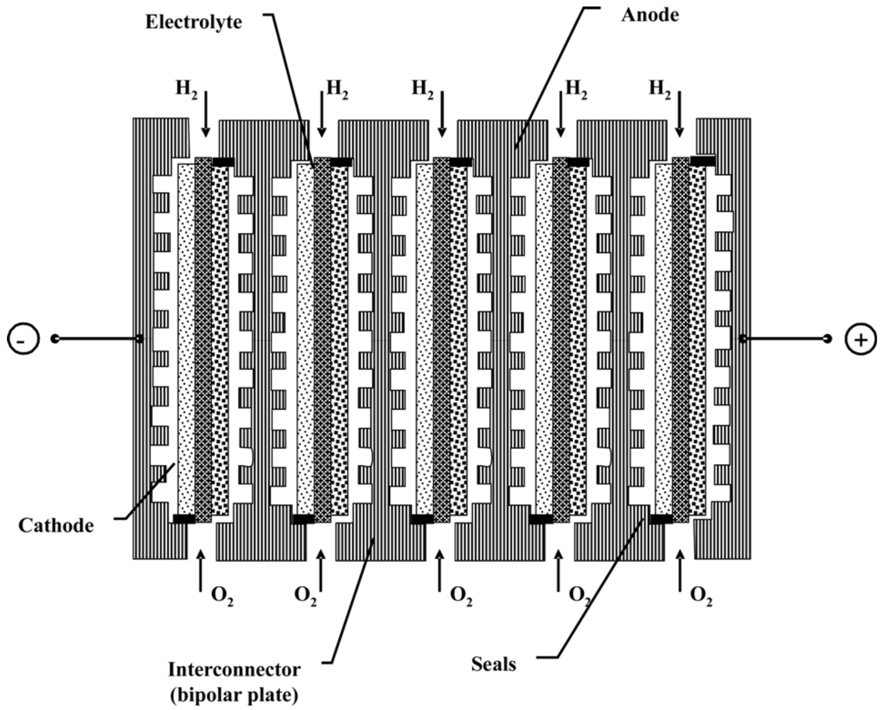

Figure 4. The bipolar SOFC of planar design.

The second stack configuration is called bipolar and is schematically presented in Fig. 4. This design is very compact and currently is most widely used in the case of planar architecture of SOFCs. This solution does not require externally bound wires. Apart from the interconnects, additional difficulties arise from the need for sealing, in order to avoid a contact between fuel and oxidant gases.

Currently one of the most important technical barriers in high-temperature fuel cell technology is the minimisation of thermal stresses that lead to cracking and thus limit the stack lifetime. Nonuniform distribution of exothermic fuel oxidation reactions leads to large thermal gradients that result in thermal stresses and thus cracking is observed. The cracking is most frequently encountered in sealing layers. Another thermal impact arises from the oxidation of the anode material under SOFC-relevant high operational temperature.

To avoid those problems two main approaches are addressed:

- thermal management, and
- temperature-resistant constructions.

Thermal management can be achieved by fuel injection policy, reducing the operating temperature of SOFCs or the involvement of heat exchange or heat recirculation [29]. Besides, especially for small SOFC assemblies (e.g., under 50 kW or even under 5 kW in which thermal losses become very significant) tight thermal integration can assure sufficiently high temperature.

In relation to thermal management an interesting disclosure is reported by Jiang *et al.* [30]. The proposes injection of hydrocarbon fuel in different locations of a fuel cell stack. When this fuel injection is appropriately monitored it allows for the minimisation of thermal gradients [31, 32] and resulting thermal stresses. In relation to temperature-resistant construction an interesting patent is reported by Chou and Stevenson [33]. It provides a double sealing layers. The first sealing layer is designed to minimise thermal stresses and the second sealing layer is intended to provide hermetic sealing.

Jiang *et al.* [30] propose a SOFC thermal management policy via direct fuel injection in different locations of the SOFC stack, Fig. 5. The invention provides structures and methods that utilise fuel reforming to assist in thermal management of a channel-less SOFC at the device cell and/or stack assembly level. At the device level, passive and/or active control of unreformed fuel, or a mixture of reformed and unreformed fuel, is used to inject fuel in a distributed manner along the anode chamber of the channel-less SOFC. The injected fuel can be controlled in its composition, pressure, velocities, and/or flow rates. Additionally, present invention provides thermal management across a plurality of fuel cells in a stack assembly by actively controlling fuel composition, pressure, velocities, and/or flow rates provided to fuel inlets of the SOFCs.

With reference to Fig. 5 one embodiment of the channel-less SOFC assembly of the present invention is depicted with respect to laterally dis-

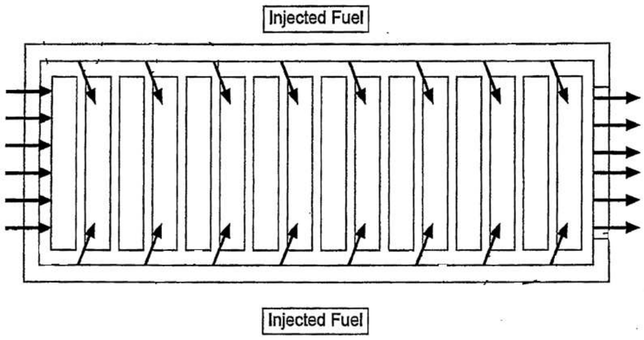

Figure 5. The schematic of the embodiment in which fuel is injected to an active area of an exemplary multi-cell SOFC laterally (horizontally) along the flow path of the primary fuel [30].

tributed fuel injection. Fuel is injected into the channel-less fuel cell assembly and is provided to the active area of the multicell device laterally (horizontally) along the flow path of primary fuel. Because the fuel chamber is not subdivided into multiple fuel channels, the fuel mixes better as it flows along the device. Because the fuel does not have to be injected into individual fuel chambers, the injection is simpler than that what is needed if each fuel channel was individually injected and because the fuel is mixed we achieve greater performance uniformity and enhanced thermal management. Similarly, a single SOFC device that forms, in combination with the frame module a single fuel chamber immediately adjacent to the SOFC device (rather than a plurality of fuel channels) may be used to form a 'channel-less' assembly. Although a SOFC device assembly may have structures within the fuel chamber for providing better support or rigidity, according to the present invention, this assembly is 'channel-less' because it does not have a plurality of fuel chambers, i.e., because the fuel provided into different portions of the fuel chamber freely mixes together.

Ogiwara *et al.* [34] propose a thermally integrated SOFC system, Fig. 6. Here, a SOFC system wherein an SOFC stack, a preliminary reformer and an integrated heat exchanger for catalytic combustion are assembled in an insulated adiabatic vessel, constituting the SOFC system in which heat losses are eliminated or reduced as much as possible. A combustion gas formed by causing combustion of the discharged fuel and discharged air, from the SOFC stack, to occur in the catalytic combustion layer is used as a heating source of the preliminary reformer after utilising the same for

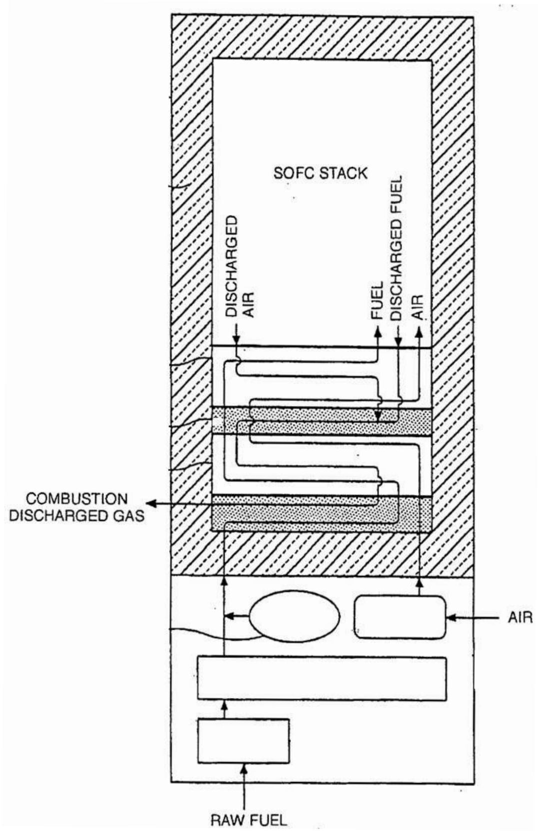

Figure 6. The scheme of the thermally integrated SOFC system [34].

preheating a reformed gas from the preliminary reformer (see Fig. 6).

Jacobson *et al.* [35] disclose a compact SOFC that offers reduction of operating temperature, Fig. 7. Reduced operating temperatures allow for the use of metallic interconnects and electrodes leading to vast cost reduction. According to the invention, the cathodes may be exposed to the air and open to the ambient atmosphere without further housing. Current collector extends through a first cathode on one side of a unit and over the unit through the cathode on the other side of the unit and is in electrical contact via lead with housing unit. Electrical insulator prevents electrical contact between two units. Fuel inlet manifold allows fuel to communicate with internal space between the anodes. Electrically insulating members prevent the current collector from being in electrical contact with the anode.

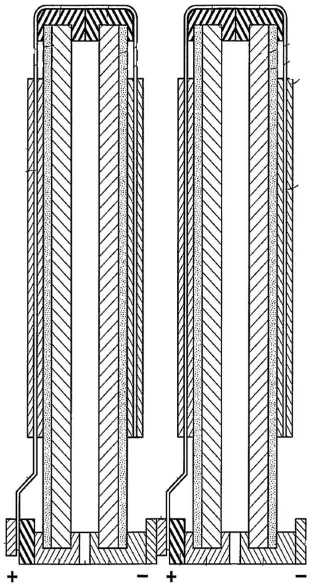

Figure 7. The cross section of the compact unit comprising two SOFCs [35].

Single-chamber SOFCs (SC-SOFCs) offer to reduce SOFC costs by downsizing and lowering the operating temperature [36]. Fuel utilisation and cell efficiency of real SC-SOFCs are usually much lower than 10% [37]. These low values can be attributed to the occurrence of parasitic side reactions in the fuel-air mixture that do not contribute to electricity generation but only to the generation of heat. Besides, thermal management of SC-SOFCs must be carefully addressed in design since the presence of hot spots at the reactor entrance can substantially increase the fuel and oxidiser conversions resulting in steep thermal gradients [38]. Current electrode materials are not selective enough to catalyse only the respective electrode reactions and fuel can be lost by the catalytic activity of the cathode materials or the complete oxidation over the anode. Transport of reaction gases from one electrode to another can impede the establishment of an open circuit voltage (OCV) [39], and gas intermixing may enhance reactions that should not be catalysed on the respective electrode. Additionally, elevated flow rates are found to yield the highest power outputs at the detriment of fuel utilisation as a large amount of fuel may pass the cell without reacting. The small size of microelectrodes can also lead to low fuel utilisation. SC-SOFCs in the tubular design seem to compensate for some of the above mentioned disadvantages. Due to the tubular cell design, gas intermixing between anode and cathode is avoided as long as a fully dense electrolyte is used. Moreover, the reaction gases have more time to react over the elongated, tubular electrodes. A fuel utilisation of 11% and an effective efficiency of approximately 5% were obtained for micro-tubular SC-SOFCs [40]. The low values for fuel utilisation and cell efficiency point out the major drawback of present SC-SOFCs and therefore the necessity to thoroughly report fuel utilisation and efficiency, which are currently omitted in most publications on SC-SOFCs. The efficiencies of the single-chamber SOFCs are generally low. Many of the reasons that account for the low efficiencies trace back to the mixing of fuel and oxygen and the one-gas-chamber geometry, which are inherent in the definition of this type of fuel cell. By applying flow management the efficiencies of SC-SOFCs can be raised only to around 5–10% [41].

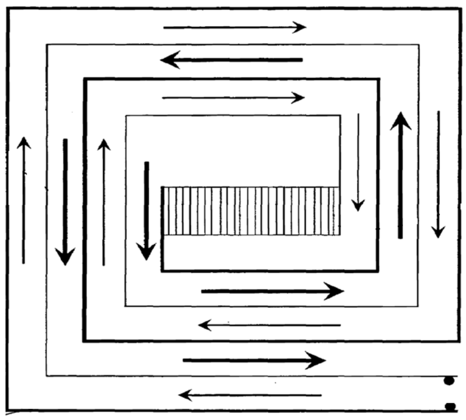

Figure 8. The scheme of the SC-SOFC surrounded by a spiral-wound counter-current heat exchanger [42].

Haile *et al.* [42] propose a SOFC with spiral-wound counter-current heat exchanger encompassing the chamber, Fig. 8. The present invention relates to a power generator and method for forming the same. More specifically, the spiral-wound counter-current heat exchanger includes a first inlet and an outlet, where both the first inlet and the outlet are connected with the chamber such that reactants introduced into the power generator flow into the first inlet and past the SOFC, where the reactants react to produce energy and reaction products. The reaction products thereafter transfer heat to the reactants and subsequently exit through the outlet. A reactor can be positioned downstream of the SOFC for converting reactants not reacted by the SOFC. An example of a design of a SC-SOFC power generator is illustrated in Fig. 8. In one embodiment, the power generator is a SOFC, surrounded by a counter-current heat exchanger spiral-wound heat exchanger which allows exiting products to transfer heat to incoming reactants.

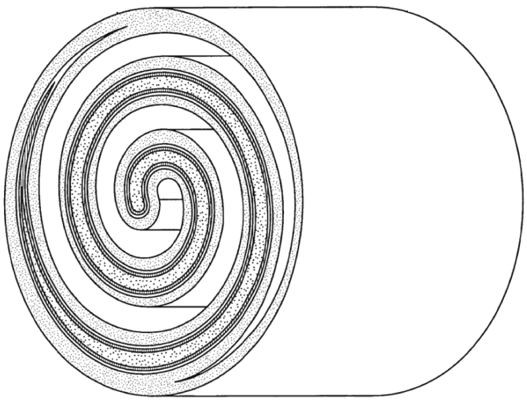

Figure 9. The perspective view of the electrochemical cell having the closed Fermat spiral shape [43].

An interesting geometry is provided by Du and Finnerty [43], Fig. 9. It relates to an electrochemical cell having a closed Fermat spiral shape. The electrochemical cell comprises an anode, a cathode, an electrolyte, a fuel channel, an oxidant channel, and optionally a reforming layer. The electrochemical cell can be made through extrusion, gel-casting, or 3D printing. The invention can be used to design SOFCs with a higher volumetric power density compared to tubular SOFCs since it offer improved power and voltage performance and fuel utilisation.

Materials employed to form various components of SOFCs, including ceramics of differing compositions, exhibit distinct coefficients of thermal expansion, thermal conductivity and strength. Problems associated with thermal stress are exacerbated when cells are stacked. As a consequence, SOFCs have limited tolerance for changes in temperature. Approaches disclosed for temperature-resistant construction include multimaterial sealing layers and special crack-free geometries. There are many technical problems that have stimulated the successful implementation of SOFCs. One problem is the need to prevent cracking of the ceramic elements during heating up the system. SOFC stacks can be susceptible to damage caused by fluctuation in temperature during their formation or use. Specifically, materials employed to form the various components, including ceramics of differing compositions, exhibit distinct coefficients of thermal expansion, thermal conductivity and strength. Problems associated with mechanical stresses caused by changes in temperature are exacerbated when individual fuel cells are stacked. Limited thermal shock resistance of fuel cells, particularly of fuel cells assembled in stacks, limits the yield of production and poses a heightened risk of failure during operation. Therefore, a need exists to minimise or eliminate the above-referenced problems.

Substantial improvements are disclosed for all SOFC geometries, however tubular geometry (monolithic, honeycomb, bundle) received increased attention.

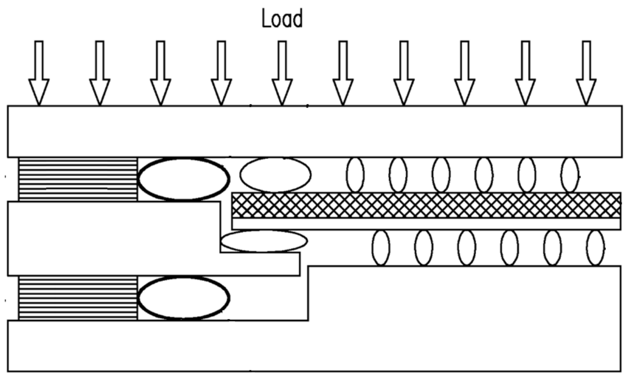

Figure 10. The scheme of the SOFC double seal with dimensional control [33].

Chou and Stevenson [33] propose a SOFC double seal with dimensional control, Fig. 10. According to the invention, the seal is a double layer having a first material with preselected characteristic and a second material with sealing characteristic. In one embodiment of the invention the first layer is a compressive material and the second one is a hermetic sealing material. In some embodiments a dimensional stabilizer may also be included as a part of the seal. In use these double seals provide superior thermal cycling stability in electrochemical devices where gases must be separated from each other.

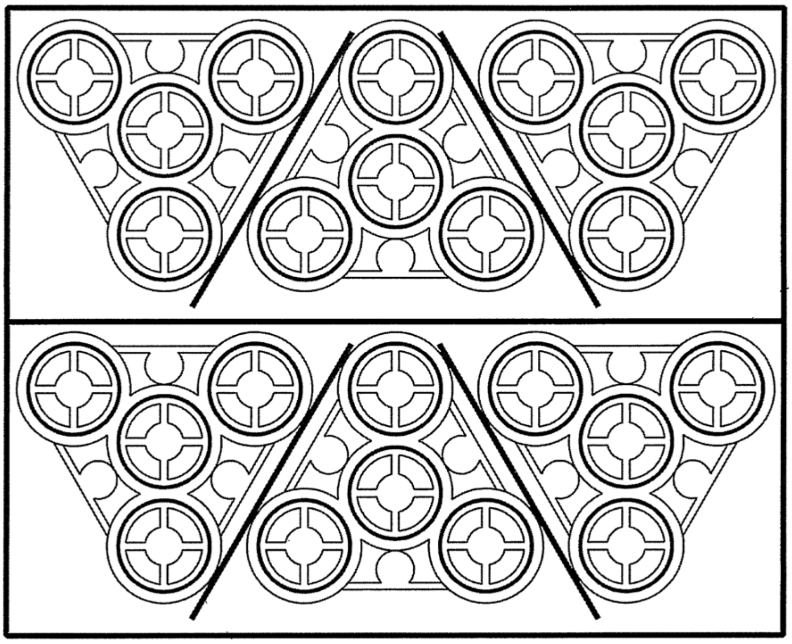

Figure 11. The scheme of the SOFC design having improved configurations for a fuel cell array [44].

Lange and Virkar [44] provide a SOFC design having stacking arrangement that allows electrical connections to be made outside of the active hot-zone, Fig. 11. Accordingly, the contacts for the positive electrode and the negative electrode are made outside the higher temperature active reaction space in a cooler area. Thus different more common materials are used which have a longer lifetime and have less stresses at their lower operating temperature. The invention utilises tubular cell components connected with spines for efficient electron transfer and at least two manifolds outside the reaction zone, which may be cooled by external means. The external protruding connectors are thus at a lower operating temperature. The adjacent cell bundles are insulated from each other by means of a refractory, electrically insulating felt. This invention improves fuel cell life span, provides for lower cost, use of more common materials, and reduces the number thermal defects during operation.

3.2 Hydrocarbons containing fuels

Hydrogen is most suitable fuel for SOFCs. Since H_2 doesn't occur in the free state in nature it must be generated from, e.g., organic fuels or from other energy sources such as solar or wind energy. The organic fuels can be converted to hydrogen by reforming. Although SOFCs can be directly fed by hydrocarbon fuels, from practical reasons such as catalyst durability, the utlisation of a reformer is usually recommended. The utilisation of a reformer is recommended. Preformed fuel enables to improve the performance of SOFCs.

The reforming of hydrocarbon fuels can be realised via internal or external mode. In the internal reforming mode fuel is reformed inside a SOFC, e.g., directly at an anode, while in the external mode fuel is reformed in an external reformer and the produced H_2-enriched gas is supplied to the anode electrode. External reformer can be either thermally integrated with a SOFC or it can function as an independent unit which is not thermally integrated. This nomenclature seems to be consistent for the description of fuel reforming in SOFCs.

Direct internal reforming of hydrocarbon fuel to hydrogen containing fuel within the stack at the SOFC anode electrode is an effective way of cooling this fuel electrode. In internal reforming an unreformed hydrocarbon fuel is provided to the anode to be reformed to a free hydrogen containing fuel, and an external reformer may be omitted. However, the reforming reaction at the anode electrode causes high local thermal stresses. The tendency is for the reforming reaction to take place very quickly upon entering the anode flow field, causing severe and in some cases catastrophic temperature gradients which could lead to SOFC failure.

Reforming of hydrocarbon fuels enables to beneficially achieve highly reactive syngas from any mixture of hydrocarbon species. It is seen that most solutions relate to the external fuel reforming which provides improved control for the reforming process. Several measures address anode off-gas recycling to a reformer. Interesting measures directed at improving SOFC performance in regards to reforming of hydrocarbon fuel include:

- internal fuel reforming,
- external fuel reforming,
- thermal integration of a reformer and a SOFC,
- anode gas recycling to a reformer,

- adjusting temperature of recycled gases,
- adjusting fuel to air ratio in a reformer,
- complete oxidation of anode off-gas,
- limited interaction between an anode and reactive reformed fuel at the anode inlet,
- catalytic anode increases fuel conversion,
- recirculation of mass and energy.

3.3 Insufficient utilisation of the fuel in the anode

Fuel utilisation can be achieved by improved species reactivity and thermal/flow characteristics. All known SOFCs are unable to achieve complete fuel conversion in the anode under standard operating conditions. Typically at the outlet from the SOFC stack the content of combustibles is above 20%. It results in decreased efficiency and adds complexity to the SOFC system necessitating the inclusion of additional equipment such as a downstream catalytic oxidiser etc.

One of the operating problems in SOFC technology is oxidation of anode tail gases. Therefore, McElroy [45] proposes a SOFC electrochemical anode tail gas oxidiser, Fig. 12. According to the invention, the SOFC system comprises a stack comprising a plurality of fuel cells and at least one shorted SOFC in which the anode is electrically connected to the cathode. In another system, at least one shorted SOFC is located downstream from a fuel cell stack. At least one shorted SOFC is positioned to receive the anode exhaust stream from at least some of the plurality of SOFCs of the fuel cell stack. According to the invention, the fuel cell system comprises a fuel cell stack comprising a plurality of fuel cells and at least one shorted solid oxide fuel cell in which the cell anode is electrically connected to the cell cathode. The shorted fuel cell oxidises tail gases which consequently can be realeased to the atmosphere.

4 Discussion

The increase of SOFC fuel-to-electricity efficiency can be attained by appropriate connections between cells that form the stack. Those connections relate to electricity and fuel flows. Optimal electrical connection is achieved when all cells are linked in series in the stack. When cells are linked in series

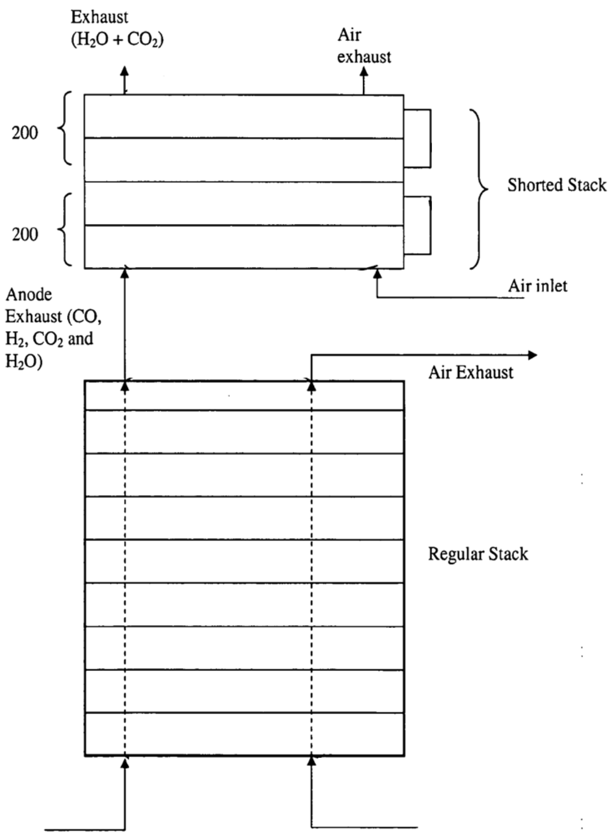

Figure 12. The scheme of the SOFC electrochemical anode tail gas oxidiser [45].

they exhibit different voltages. On the contrary, when cells are linked in parallel all cells exhibit the same voltages equal to the lowest one. Consequently, connections in series enable to achieve higher voltage of the whole stack at the same generated current, which results in increased efficiency. The most beneficial configuration of fuel flow (at the anode side) is also in series, i.e., the fuel outlet from one cell is the inlet to the next one. It results in increased fuel utilisation and consequently in increased fuel-to-electricity efficiency. In contrast, the beneficial oxidiser flow is that in parallel, i.e., when the oxidiser entering each cell has the same parameters.

Measures to increase fuel-to-electricity efficiency reffer to several SOFCs utilise configurations characterised by in series electrical connections, in series fuel flow path and in parallel oxidiser flow path. Interesting measures that can increase fuel-to-electricity efficiency are linked with:

- in series electrical connections,
- in series fuel flow path and in parallel oxidiser flow path,
- improved switching possibilities,
- decreased ohmic losses through configuration or material,
- recycling of anode off-gas,
- fuel reforming,
- inclusion of gas turbine in a hybrid system,
- inclusion of heat recovery,
- high-pressure SOFC operation,
- segmented stack,
- forcing fuel flow through the anode electrode and
- uniform gas supply.

4.1 Thermal management

Thermal management relates to the control of temperature in a SOFC. Control policy must assure sufficiently high temperature to enhance reactions and ion transport through an electrolyte. Besides, steep local thermal gradients or excessive temperatures must be avoided. Interesting measures of thermal management include:

- fuel injection in different locations,
- the integration of a SOFC with an endothermic reformer and
- its integration with a heat exchanger,
- the inclusion of thermal enclosure around exo- and endothermic subunits,
- recirculation of mass and energy,
- the use of reduced operating temperatures and
- the involvement of a single-chamber configuration.

Temperature-resistant construction is achieved through the use of novel cracking- and oxidation-resistant materials, location of nonresistant parts outside hot zones, avoidance of thermal gradients or excessive temperatures and limiting the contact of species with excessive oxidative potential with a cell. Several measures address SOFC having characterised by crack-free geometry. Interesting measures that improve SOFC technology include:

- the use of materials with various compositions reducing thermal stresses,
- avoiding of anode oxidation,
- preventing contacting of reactive fuel with electrolyte,
- crack free geometry,
- electrical connections made outside the hot zone and
- stack insulation.

4.2 Fuel utilization

The most frequently used technique is the recirculation of anode off-gas back to the reformer. However, the recirculation of hot anode tail gases results in increased pressure drops over the stack and thus auxiliary pumping equipment is needed. Anode off-gases are recycled by means of a jet pump but also the use of a fan has been reported.

Measures to increase the utilisation of fuel in the SOFC anode include:

- recirculation of anode off-gas back to the reformer,
- H_2 separation,
- water recycle,
- auxiliary SOFC for anode off-gas oxidation
- venting anode off-gas,
- H_2 generation from anode off-gas,
- recirculation of unreformed fuel – system mass integration and
- catalytic anode.

5 Conclusions

The article showed that a significant progress in the SOFC technology was made during the last few years. Disclosed measures addressed four key technical barriers that currently limit deployment opportunities of SOFC technology, especially for large-scale power generation:

(i) insufficient thermal resistance,

(ii) complexity arising from the need for reforming of hydrocarbon fuels,

(iii) insufficient overall energy efficiency of SOFC stacks and,

(iv) insufficient utilisation of the fuel in the anode.

Achieved advances arose from improved fuel policies, thermal management, novel materials and geometries. Especially considerable progress was achieved in hybrid systems and in the SOFCs of tubular design. In the future, further development of SOFCs is strongly needed. Main emphasis must be put on the overall cost reduction, including SOFC manufacture, operation and costs of electricity. Novel materials for SOFCs must be developed addressing temperature-resistant construction and catalytic reactivity. New process intensification techniques and consistent design approaches such as that based on nonequilibrium thermodynamics will be necessary in order to improve energy conversion efficiency by using SOFCs. The interest in the application of SOFCs in hybrid systems will grow. Therefore studies aimed at the integration of SOFC-based power generators will be also needed. Furthermore, increased power density and new possibility of reducing the operating temperature below 800 °C will be addressed. A consolidation of activities will be observed, especially in the United States and Japan due to the increased involvement of SOFC technology by industry. The interest in using SOFCs in large-scale decarbonised hybrid systems linked with hydrocarbons splitting into H_2 and CO_2 such as the decarbonised oxy-reforming fuel cell is expected. The near-term commercial focus will be on small SOFC units in the kW range for residential energy supply and up to several 10 kW for small- to medium-sized CHP applications.

Acknowledgements W.M. Budzianowski gratefully acknowledges the financial support from Wrocław University of Technology under the grant No. 344069 Z0311.

Received 26 May 2011

References

[1] Budzianowski W.: *Negative net CO_2 emissions from oxydecarbonization of biogas to H_2*. Int. J. Chem. React. Eng. **8**(2010), A156.

[2] Muradov N., Veziroglu T.: *'Green' path from fossil-based to hydrogen economy: an overview of carbon-neutral technologies*. Int. J. Hydrogen Energ. **33**(2008), 6804–6839.

[3] Panayiotou G., Kalogirou S., Tassou S.: *Solar hydrogen production and storage techniques*. Recent Pat. Mech. Eng. **3**(2010), 154–159.

[4] Yilanci A.,Dincer I., Ozturk H.: *A review on solar-hydrogen/fuel cell hybrid energy systems for stationary applications*. Prog. Energ. Combust. **35**(2009), 231–244.

[5] Kee R., Zhu H., Sukeshini A., Jackson G.: *Solid oxide fuel cells: operating principles, current challanges, and the role of syngas*. Combust. Sci. Technol. **180**(2008), 1207–1244.

[6] Milewski J.,Lewandowski J.: *Solid oxide fuel cell fuelled by biogases*. Arch. Thermodyn. **30**(2009), 4, 3–12.

[7] Budzianowski W.: *An oxy-fuel mass-recirculating process for H_2 production with CO_2 capture by autothermal catalytic oxyforming of methane*. Int. J. Hydrogen Energ. **35**(2010), 7754–7769.

[8] Milewski J., Miller A., Sałacinski J.: *Off-design analysis of sofc hybrid system*. Int. J. Hydrogen Energ. **32**(2007), 6, 687–698.

[9] Zhang H., Lin G., Chen J.: *Performance analysis and multiobjective optimization of a new molten carbonate fuel cell system*. Int. J. Hydrogen Energ. **36**(2011), 6, 4015–4021.

[10] Badyda K.: *Characteristics of advanced gas turbine cycles*. Rynek Energii **88**(2010), 3, 80–86 (in Polish).

[11] Mueller F., Gaynor R., Auld A., Brouwer J., Jabbari F., Samuelsen G.G.S.: *Synergistic integration of a gas turbine and solid oxide fuel cell for improved transient capability*. J. Power Sources **176**(2008), 1, 229–239.

[12] Tarroja B., Mueller F., Maclay J., Brouwer J.: *Parametric thermodynamic analysis of a solid oxide fuel cell gas turbine system design space*. In: Proc. ASME Turbo Expo **2**(2008), 829–841.

[13] Tarroja B., Mueller F., Maclay J., Brouwer J.: *Parametric thermodynamic analysis of a solid oxide fuel cell gas turbine system design space*. J. Eng. Gas Turb. Power **132**(2010), 7, 072301.

[14] Wu W., Luo J.-J.: *Nonlinear feedback control of a preheaterintegrated molten carbonate fuel cell system*. J. Process Contr. **20**(2010), 7, 860–868.

[15] Al-Sulaiman F., Dincer I., Hamdullahpur F.: *Energy analysis of a trigeneration plant based on solid oxide fuel cell and organic Rankine cycle*. Int. J. Hydrogen Energ. **35**(2010), 10, 5104–5113.

[16] Budzianowski W.: *Thermal and bifurcation characteristics of heat recirculating conversion of gaseous fuels*. Arch. Thermodyn. **31**(2010), 2, 63–75.

[17] Lanzini A., Santarelli M., Orsello G.: *Residential solid oxide fuel cell generator fuelled by ethanol: Cell, stack and system modelling with a preliminary experiment*. Fuel Cells **10**(2010), 4, 654–675.

[18] Sciacovelli A., Verda V.: *Entropy generation minimization in a tubular solid oxide fuel cell*. J. Energ. Resour. **132**(2010), 012601.

[19] Kjelstrup S., Coppens M., Pharoah J., Pfeifer P.: *Nature-inspired energy- and material-efficient design of a polymer electrolyte membrane fuel cell*. Energy Fuel **24**(2010), 5097–5108.

[20] Sciacovelli A., Verda V.: *Entropy generation analysis in a monolithic-type solid oxide fuel cell (SOFC)*. Energ. **34**(2009), 850–865.

[21] Milewski J., Badyda K., Misztal Z., Wołowicz M.: *Combined heat and power unit based on polymeric electrolyte membrane fuel cell in a hotel application*. Rynek Energii **90**(2010), 118–123.

[22] Colombo K., Kharton V., Bolland O.: *Simulation of an oxygen membrane-based gas turbine power plant: Dynamic regimes with operational and material constraints*. Energ. Fuel. **24**(2010), 1, 590–608.

[23] Christman K., Jensen M.: *Solid oxide fuel cell performance with cross-flow roughness*. J. Fuel Cell Sci. Techn. **8**(2011), 2, 024501.

[24] Cao H., Deng Z., Li X., Yang J., Qin Y.: *Dynamic modeling of electrical characteristics of solid oxide fuel cells using fractional derivatives*. Int. J. Hydrogen Energy **35**(2010), 4, 1749–1758.

[25] Cao H., Li X., Deng Z., Jiang J., Yang J., Li J., Qin Y.: *Dynamic modeling and experimental validation for the electrical coupling in a 5- cell solid oxide fuel cell stack in the perspective of thermal coupling*. Int. J. Hydrogen Energg. **36**(2011), 7, 4409–4418.

[26] Hajimolana S., Hussain M., Daud W., Soroush M., Shamiri A.: *Mathematical modeling of solid oxide fuel cells: A review*. Renew. Sust. Energ. Rev. **15**(2011), 4, 1893–1917.

[27] Kishor N., Mohanty S.: *Fuzzy modeling of fuel cell based on mutual information between variables*. Int. J. Hydrogen Energ. **35**(2010), 8, 3620–3631.

[28] Sisworahardjo N., Yalcinoz T., El-Sharkh M., Alam M.: *Neural network model of 100 W portable pem fuel cell and experimental verification*. Int. J Hydrogen Energ. **35**(2010), 17, 9104–9109.

[29] Budzianowski W.: *Thermal integration of combustion-based energy generators by heat recirculation*. Rynek Energii **91**(2010), 6, 108–115.

[30] Jiang Y., Pollard S., Julien D., Tanner C.: *WO Patent 2 007 126 588A2* 2007.

[31] Budzianowski W.: *Non-stationary catalytic combustion over a catalyst with internal temperature gradients*. Arch. Combust. **25**(2005), 7–15.

[32] Budzianowski W., Koziol A.: *Determination of parameters of a catalyst particle in non-stationary conditions*. Chem. Process Eng. **25**(2004),751–756.

[33] Chou Y.-S., Stevenson J.: *WO Patent 2 009 155 184A1*, 2009.

[34] Ogiwara T., Matsuzaki Y., Yasuda I., Ito K.: *EP Patent 2 244 327A1*, 2010.

[35] Jacobson C., Dejonghe L., Lu C.: *US Patent 7 816 055B2*, 2010.

[36] Yano M., Tomita A., Sano M., Hibino T.: *Recent advances in single-chamber solid oxide fuel cells: A review*. Solid State Ionics **177**(2007), 3351–3359.

[37] Kuhn M., Napporn T.: *Single-chamber solid-oxide fuel cell technology – from its origin to todayñs state of the art (review)*. Energies **3**(2010), 57–134.

[38] Savoie S., Napporn T., Morel B., Meunier M., Roberge R.: *Catalytic activity of ni-ysz anodes in a single chamber solid oxide fuel cell reactor*. J. Power Sources **196**(2011), 3713–3721.

[39] Shao Z., Haile S., Ahn J., Ronney P., Zhan Z., Barnett S.: *A thermally self-sustained micro solid-oxide fuel-cell stack with high power density*. Nature **435**(2005), 795–798.

[40] Akhtar N., Decent S., Loghin D., Kendall K.: *Mixed-reactant, micro-tubular solid oxide fuel cells: An experimental study*. J. Power Sources **193**(2009), 39–48.

[41] Hao Y., Goodwin D.: *Efficiency and fuel utilization of methanepowered single-chamber solid oxide fuel cell*. J. Power Sources **183**(2008), 157–163.

[42] Haile S., Ronney P., Shao Z.: *US Patent 20 077 247 402B2*, 2007.

[43] Du Y., Finnerty C.: *WO Patent 2 009 061 294A1*, 2009.

[44] Lange F., Virkar A.: *WO Patent 2 007 005 767A1*, 2007.

[45] McElroy J.: *US Patent 20 090 208 785A1*, 2009.