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Novel applications for micro-SOFCs

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Abstract

The application of micro-solid oxide fuels cells in small systems is discussed. Two types of application are examined, namely, leisure CHP systems and micro-hybrid vehicles. A unique triple layer catalyst–SOFC–catalyst system has been designed utilising propane/butane fuel. The system consists of a co-generating gas burner with a pre-reforming catalyst, a micro-SOFC stack and an oxidation catalyst. The pre-reforming catalyst comprising of Ru metal on Saffil® ceramic wool, was used to partially reform the propane/butane gas prior to entering the fuel cell, preventing carbon formation. The micro-SOFCs were YSZ tubes (Adelan, UK) with nickel/YSZ cermet anodes on the outside and strontium-doped lanthanum manganite cathodes on the inside. Final oxidation was provided by a cordierite honeycomb coated with platinum combustion catalyst producing most of the heat for the fuel cell operation. Initial performance results were obtained and it was shown that a co-generating system could be achieved using a propane/butane fuel supply, piezoelectric ignition system and air supply for the triple catalyst system. The application of this micro-SOFC system for leisure and micro-hybrid vehicles, such as golf trolleys and power-assisted bicycles, is described.

Keywords: Micro-SOFC; Combined heat and power; Leisure application; Micro-hybrid vehicle

1. Introduction

Micro tubular solid oxide fuel cells, as described by Kendall and Sales [1] and Kilbride [2], are fabricated using yttria stabilised zirconia, extruded and fired to form 2 mm diameter, 200 μm wall thickness electrolyte tubes that can be painted with nickel/YSZ cermet anodes and strontium-doped lanthanum manganite cathodes, giving excellent thermal shock resistance. This has been successfully demonstrated with small Adelan® cells [3,4], and larger stacks consisting of 200 and 1000 cells at Keele University [5,6].

The objective here is to show that these cells can be used inside a novel 3-catalyst burner system to generate combined heat and power (CHP) from propane/butane fuels. This system is the simplest yet devised for the direct use of hydrocarbons in a fuel cell device [7,8]. It is intended to demonstrate this system in the recreational market where novel and useful applications may be significant. For example, camping caravans and sports activities make use of propane/butane (camping gas) and a fuel cell CHP system would be extremely useful in those applications. SOFCs have not previously been considered for such small applications [9]. On the other hand, PEMs have been extensively studied for applications such as portable telecommunications [10], electronics [11], medical [12] and transportation [13–15]. The use of fuel cells in vehicle applications has accelerated in recent years, particularly the application of polymer electrolyte membrane (PEM) fuel cell systems, such as those produced by Ballard Power Systems. Pre-reforming of hydrocarbons for use in SOFCs has been well reported [16,17], however, little literature exists on the combined use of catalytic burners and fuel cells. Cargnelli et al. [18] reported the use of a flameless catalytic hydrogen burner to provide electricity via a thermoelectric generator and warm, moist air for a PEM fuel cell. A core temperature of 350°C can be achieved with natural convection and this temperature was achieved in less than 10 s. The core temperature is mainly regulated by the gas flow rate.

There exist many small vehicle applications requiring less than 1 kW capacity, such as bicycles and scooters. Leisure and small hybrid vehicle applications are under development by several different companies and institutes,

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primarily utilising polymer electrolyte membrane fuel cell (PEM) technologies. An example of a small hybrid vehicle is the hydrogen fuel cell golf carts developed by SERC. These have been in use in Palm Springs, California since late 1996 [19]. In such a hybrid vehicle, a fuel cell and lead acid battery is combined to produce the power. Smaller vehicular usage of fuel cells has not been investigated to any great extent for electric golf trolleys, bicycles, and little work exists on micro-SOFC applications.

In this paper, we describe the possible applications of micro-SOFCs for CHP leisure uses and for hybrid vehicles.

2. Combined heat and power device design

2.1. Gas and heat flow in the CHP system

A heat and power generating device was designed based on retrofitting a catalytic gas burner with a micro-SOFC stack for electricity generation, and a pre-reformer to provide hydrogen conversion (and heat) for the fuel cell operation. Fig. 1 shows a diagram of the gas and heat flows in the triple layer catalyst–SOFC–catalyst system. The propane/butane fuel is initially mixed with air to provide both fuel and oxidant for combustion. The Pt combustion catalyst provides heat, by burning the fuel at up to 900°C, for both the fuel cell operation and to pre-heat the Ru pre-reforming catalyst. The catalytic reformer produces hydrogen gas for the fuel cell operation and the air content in the gas prevents carbon build up on the fuel cell anodes, by oxidising the carbon. Heat is also produced from the electrochemical reactions occurring on the pre-reformer and fuel cell tubes, with the pre-reforming operating optimally at ca. 700°C. Finally, the air that is utilised in the fuel cells is fed back to the pre-burner fuel mix to preheat the fuel giving a faster reaction time.

2.1.1. Construction of the co-generating gas burner

The micro-SOFCs were yttria stabilised zirconia (YSZ) tubes (Adelan®, UK) with nickel/YSZ cermet anodes on the outside and strontium-doped lanthanum manganite cathodes on the inside using compositions and fabrication routes as described by Kilbride [2]. However, a second anode layer was present which contained 5 wt.% CeO_2 mixed with the nickel/YSZ cermet.

The top of the honeycomb combustion catalyst tray of the Camping Gaz® burner was removed. Holes of ca. 5 mm diameter where drilled in each side above the level of catalyst (see Fig. 2). Using a ceramic cement (Autostic™,

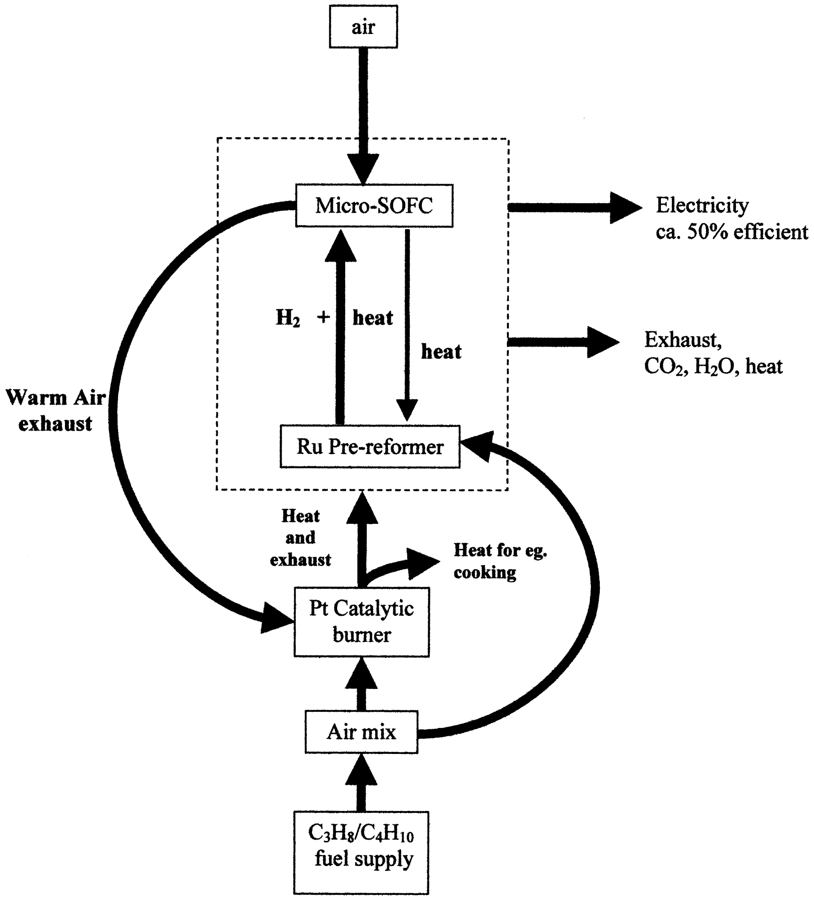

Fig. 1. Flow diagram of the gas and heat exchanges in the triple layer catalyst–SOFC–catalyst cogeneration system.

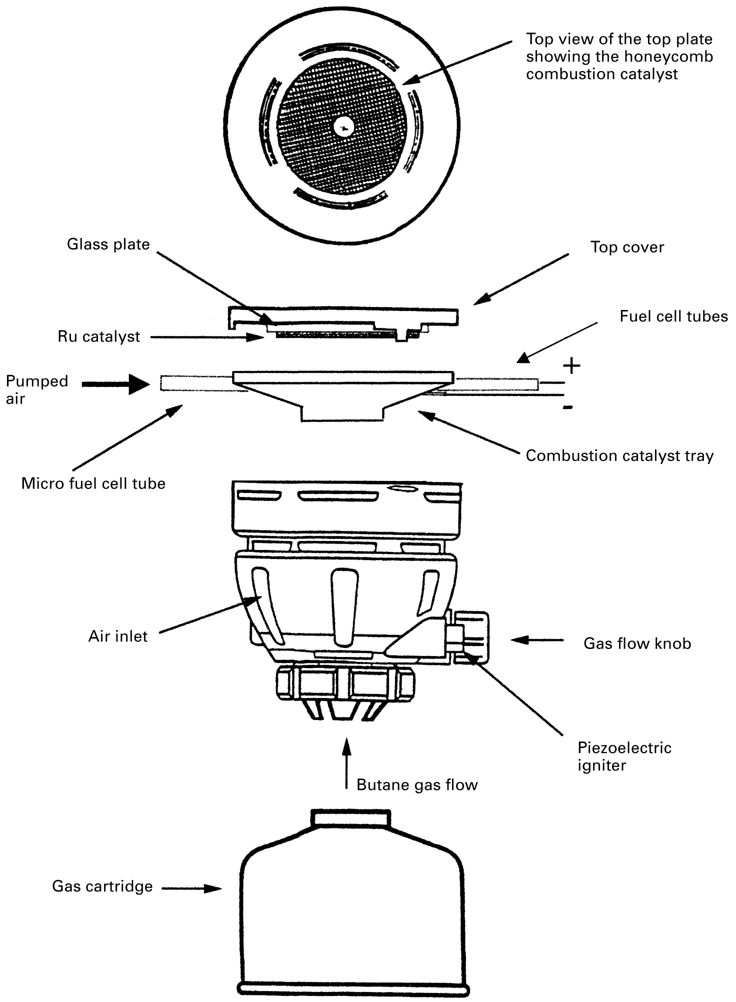

Fig. 2. Schematic of the Camping Gaz® burner components, showing the position of the micro-SOFC.

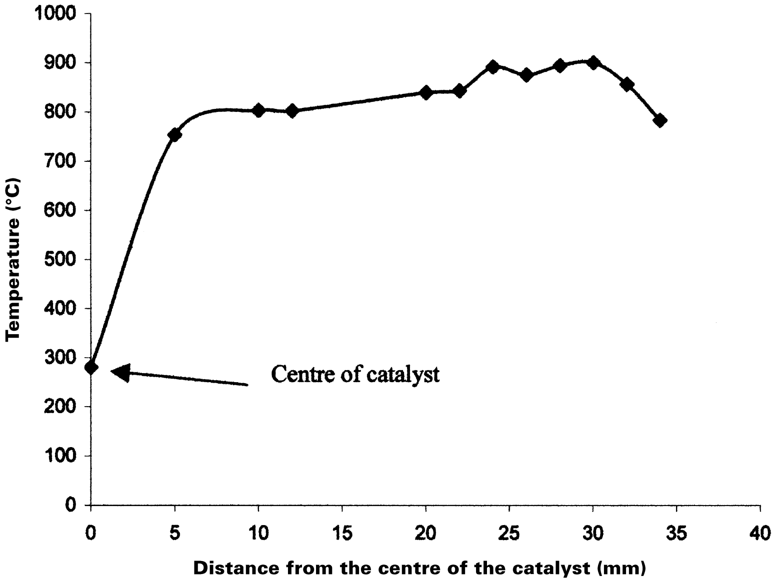

Fig. 3. Graph of temperature changes across the combustion catalyst under operation.

Table 1
Triple catalyst–SOFC catalyst system performance indicators

OCV (stack in parallel) (mV)	Gas flow	Pre-reforming catalyst present
11	High	No
271	Low	No
898	Low	Yes
947	Low	Yes

Carlton Brown and Partners) the fuel cell tubes were cemented 1 mm above the honeycomb catalyst. The Ru on Saffil® catalyst was attached to the underside of the glass lid top using metal screw clamps.

2.1.2. Performance of the co-generating gas burner

In order to ascertain the power output and performance of the fuel cell stack in the gas burner, the cells were first wired in parallel. The gas flow was turned to high and ignited using the piezoelectric igniter. The gas flow was adjusted using a control valve and first passed through a pre-mix orifice where air and butane were mixed. The gas impinged on the bottom of the glass lid/pre-reforming catalyst and then on the fuel cells and the combustion catalyst, where it was burnt. The gas took a few seconds to heat the combustion catalyst to a red glow, which then heated the fuel cells and the pre-reforming catalyst. The voltage was monitored using a multimeter while the gas flow and pre-reformer condition were altered to observe their effect on the stack performance.

Preliminary stack performance was studied as the component in the triple layer catalyst–micro SOFC–catalyst gas burner system. A thermocouple was placed near the centre of the combustion catalyst radius under the fuel cell tubes and the temperature measured across the radius to determine the thermal distribution under working conditions. Fig. 3 shows the graph of temperature vs. position across the catalyst radius. It can be seen that from Fig. 3, that there is a plateau of temperature above 800°C between ca. 10 and 30 mm from the centre of the combustion catalyst. This temperature is sufficient for fuel cell operation. The cooler region in the centre (<5 mm) of the combustion catalyst is due to the cool gas inlet flow.

A multimeter was used to record the OCV of the fuel cell stack. The total stack voltage was recorded for different conditions of high and low gas flow and the presence of the pre-reforming catalyst (shown in Table 1). The presence of the pre-reforming catalyst and low gas flows were essential to produce a significant open circuit voltage of close to 1 V. The high gas flows may cause cooling of the fuel cell tubes affecting the performance, whereas the pre-reformer will catalyse the hydrocarbon fuel to hydrogen giving better fuel cell performance. A small musical speaker was also applied to the stack and sufficient power

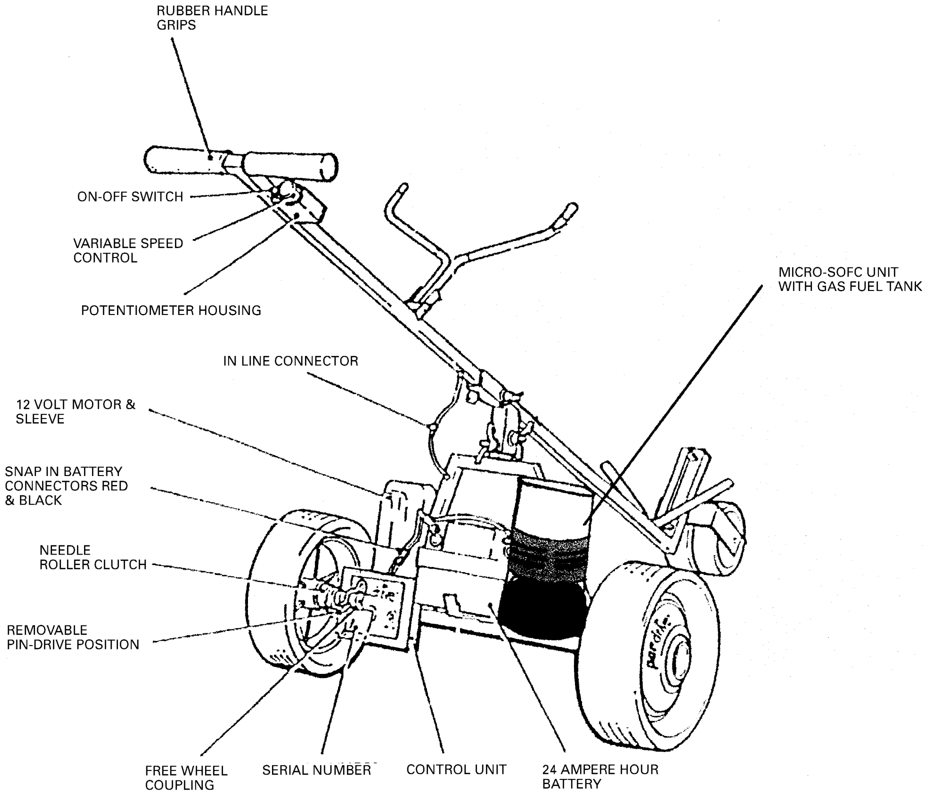

Fig. 4. Schematic of the Par Drive Eagle electric golf trolley showing the position and approximate size of a possible micro-SOFC system.

Table 2
Power, charge time, price and battery and/or fuel cell specifications for various commercial and prototype applications

Application (company)	Power required	Battery or fuel cell system	Charge time, lifetime	Price (£)	Reference
Camping gas burner (Camping Gaz)		Propane/butane gas cartridge	ca. 30 h, 500 ml cartridge	30	[24]
Electric Golf Trolley (ParDrive)	60 W electric motor	12 V, 24 Ah lead acid	48 h charge, ca. 3 h use to 80% charge	500	[25]
Power-assisted bicycles					
Electric Trike (Crystal Engineering)	200 W (TGA Electric leisure)	2 × 17 Ah lead acid	48 h full charge, 32 km range (open road)	2450 (with trike)	[26]
Electric bicycle XPC26 (Yamaha/Bridgestone)	235 W	24 V 5 Ah NiCad	3.5 h charge, 28 km range	523 (with bike)	[27]
Hub electric motor (Heinzmann)	400 W	24 V NiCad	2 h 50 min charge, 20 km range	350 700 (with bike)	[28]
ZAP DX kit (Domain)	300 W	20 Ah lead acid	4 h charge, 32 km range	350	[29]
ZAP SX kit (Domain)	400 W	20 Ah lead acid	3 h charge, 24 km range	380	[28]
Fuel cell trike, Power PEM-EV200H (H-Power)	200 W	24 V PEM	Metal hydride, 420 L H_2	Prototype only	[22]
Wheelchair, Power PEM-200H (H-Power)	200 W	24 V PEM, 1.6 Ah NiCad (21 cell)	Metal hydride, 420 L H_2	Prototype only	[22]

was produced to operate this speaker rated at 1.5 W. With better performance cells, the power output will increase. Air was forced using a small pump, though the tubes via silicone manifolding, however this did not affect the stack performance significantly. No significant carbon formation was observed on the SOFC anodes, however, delamination occurred after successive thermal cycling.

3. Micro-hybrid vehicle applications

3.1. Electric golf trolley

Par Drive produce an electric golf trolley shown in Fig. 4. This trolley utilises a 12 V, 60 W motor and a 24 Ah lead acid battery supplies enough power for a single 18 hole game on a 48-h full charge. The charge time is of considerably longer duration compared to the useful running time (ca. 3 h to 20% charge). Application of a micro fuel cell system would provide several advantages namely,

Fig. 5. Crystal Engineering Trice electric tricycle.

Fig. 6. (a) H-Power fuel cell power assisted bicycle and (b) tricycle in action.

when used in combination with a battery cell, the power efficiency is greatly increased, with the battery taking the peak loads [20]. The fuel cell could be used to recharge the battery and the battery life would be extended due to smaller discharge depth ultimately reducing the costs of the number of replacements. The usable time would be increased due to the continuous recharging from the fuel cell, when in use. Fig. 4 shows a schematic of the electric golf trolley with a micro-SOFC charging system attached to the right side to balance with the weight of the motor. The total weight of the micro-SOFC and butane/propane tank (450 g cartridge) is ca. 1.5 kg, which is comparatively small when compared to the electric motor and lead acid battery. Therefore, the total weight of the trolley is not increased a great deal; however the battery lifetime can by extended considerably.

3.2. Power-assisted bicycles

Alternatives to the polluting, combustion-engined automobile are necessary for the future sustainability and health of cities around the globe. Power assisted bicycles (PABs) are a cheap, efficient transportation mode and are now increasingly popular in countries such as Japan and The Netherlands [21]. People use them to do the shopping and carry small children, and they offer an alternative transport mode for injured people. Typically, PABs are powered by either lead acid or NiCad batteries, with motor power ratings of between 200 and 400 W, depending on the make and type (see Table 2). Both two and three wheeled cycles are available on the market with power assistance. An example of a three wheeled electric power assisted recumbent produced by Crystal Engineering, UK, is shown in Fig. 5. These electric recumbents use a 200 W motor powered by two 17 Ah lead acid batteries. As discussed with the electric golf trolley, the implementation of a hybrid battery-micro fuel cell system is feasible for application to electric cycles. The fuel cell could be used to directly power the motor or more likely charge the battery while the battery drives the motor. H-Power [22] has recently built PEM based fuel cell powered bicycles and tricycles as shown in Fig. 6(a) and (b), respectively, as well as a wheelchair. Both the power-assisted cycles and wheelchair have a power rating of 200 W and include a NiCad battery for start up. Hydrogen fuel is utilised from a 420-l metal hydride storage tank. The price range varies depending on the make and power, and the prices are included in Table 1 to give an indication of the significant costs that are afforded for leisure vehicle items.

4. Conclusions

The initial design and construction of a co-generating gas burner incorporating a pre-reforming catalyst and a micro-SOFC stack, was undertaken. The camping gas burner used was from Camping Gaz®, who have marketed a novel gas burner for outdoor cooking use, utilising a Pt-coated honeycomb catalyst to combust the butane fuel instead of the typical flame burner system. A pre-reforming catalyst comprising of Ru metal on Saffil® ceramic wool, was used to partially reform the butane gas prior to the fuel cell, greatly improving the OCV and power output. Initial performance results were obtained and it was shown that a co-generating system could be achieved using a micro-SOFC stack coupled with a pre-reformer in a catalytic gas burner. Improvements in design and fuel cell performance are currently in progress [23].

The application of this catalyst-SOFC-catalyst system for leisure cogeneration of heat and power, and for the use in micro hybrid electric vehicles is feasible.

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