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Personal power using metal-supported solid oxide fuel cells operated in a camping stove flame

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ABSTRACT

A complete stand-alone product prototype providing combined cooking and power is fabricated by retrofitting a commercial camping stove with a stack of metal-supported solid oxide fuel cells (MS-SOFCs) delivering power to microelectronic LED driver and voltage boost circuits. The 5-cell stack produces 2.7 W (156 mW cm^{-2}) while cooking on the stove, and is demonstrated to produce LED lighting and mobile phone charging while operating outdoors. Cooking efficiency is minimally impacted by the presence of the MS-SOFCs. It is found that vertical orientation of the cells is critical to maintain separation of fuel and air when a pot is placed on the stove.

Introduction

Solid oxide fuel cells (SOFCs) operate at elevated temperature, typically 600–900 °C, and require electrochemically-active fuel such as H_2 or CO to produce power. An extremely simple way to fulfill these requirements is to place the anode of the SOFC in contact with a flame, which provides the necessary heat and contains H_2 and CO within the primary combustion zone. This "direct-flame" setup yields relatively low performance and very low fuel-to-power efficiency, but has been studied extensively in the literature due to the simplicity and appeal of the system; no costly balance of plant is required to produce power [1–29]. Direct-flame SOFCs have been operated with a variety of gaseous, liquid, and solid fuels, including methane [2], propane [6], butane [4], ethylene [5], ethanol [15], methanol [8], parrafin [4], and wood [4]. A wide variety of burner configurations have been implemented, including jet burner tube which provides a simple setup and stable flame [19], micro-jet flame [7], multi-element diffusion flame burner [16], and flat flame burner [28] which provides very uniform temperature and concentration distributions across the cell area. Applications including an integrated multi-cell microtubular stack [13,23], and a tri-generation system for power, heating, and cooling has been analyzed [27], and deployment can be envisioned anywhere that flames are available, including industrial heating, residential water heating, and well-head gas flares. Low electrical efficiency is expected for such scenarios, as much of the fuel is combusted to produce heat, but the direct flame configuration can provide electricity where none is otherwise available.

Metal-supported SOFCs (MS-SOFCs) are particularly well suited to direct-flame operation due to their tolerance to thermal cycling and anode re-oxidation, and provide additional benefits including low materials cost, mechanical ruggedness, and in some cases high power density [30–32].

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The MS-SOFC architecture shown in Fig. 1 is symmetric, with porous stainless steel supports and porous YSZ electrode layers bonded to both sides of the YSZ electrolyte. Nano-scale catalysts are introduced into both electrodes by infiltration, as described in recent work [33]. In preparation for the prototype demonstration presented here, the performance of MS-SOFC in propane direct-flame configuration was systematically mapped over a wide range of flame operation parameters, including burner-to-cell gap height, equivalence ratio, and flow velocity, using a tubular burner as shown in Fig. 1d [34]. High power, 633 mW cm^{-2} at 833 °C, was achieved under controlled and optimized conditions.

An interesting application of the direct-flame configuration is portable personal power achieved by inserting SOFCs into the flame of an operating cooking stove. Simple proof-of-concept prototypes of this design have been fabricated previously. A small camping stove with isopropane-butane fuel was fitted with 10 small MS-SOFCs in series, mounted horizontally above the burner face, and providing power to a USB port with no power conditioning electronics; performance was not reported [35]. A butane camping stove was fitted with 3 small anode-supported cells (ASC) each 0.8 cm^2, mounted horizontally above the burner face, and joined in series by silver paste and wires [20]. The stack was heated up in about 10 min, provided 0.24 W (0.1 W cm^{-2}), and was used to power a small fan. Multiple thermal cycles were not reported, but it is expected that such small ASCs would survive if the heating and cooling rates are sufficiently slow. Here, we improve upon the earlier demonstrations by: fabricating a stack of larger MS-SOFCs that provides an order of magnitude higher power; using low-cost materials to join the cells; designing the stack to be coupled with high-efficiency power electronics for LED lighting and mobile phone charging; and, overcoming challenges associated with producing power while simultaneously cooking.

Experimental methods

Details of the cell fabrication and catalyst infiltration procedures are discussed elsewhere [33]. MS-SOFCs were fabricated from YSZ (8Y, Tosoh) and stainless steel (P434L alloy, water atomized, Ametek Specialty Metal Products) layers prepared by tape-casting. Individual tapes were laminated together to create the green cell structure. Cells were cut from the layered tape with a laser cutter (H-series, Full Spectrum Laser). Cells were debinded in air at 525 °C for 1 h, and then sintered in 2% hydrogen in argon at 1350 °C for 2 h in a tube

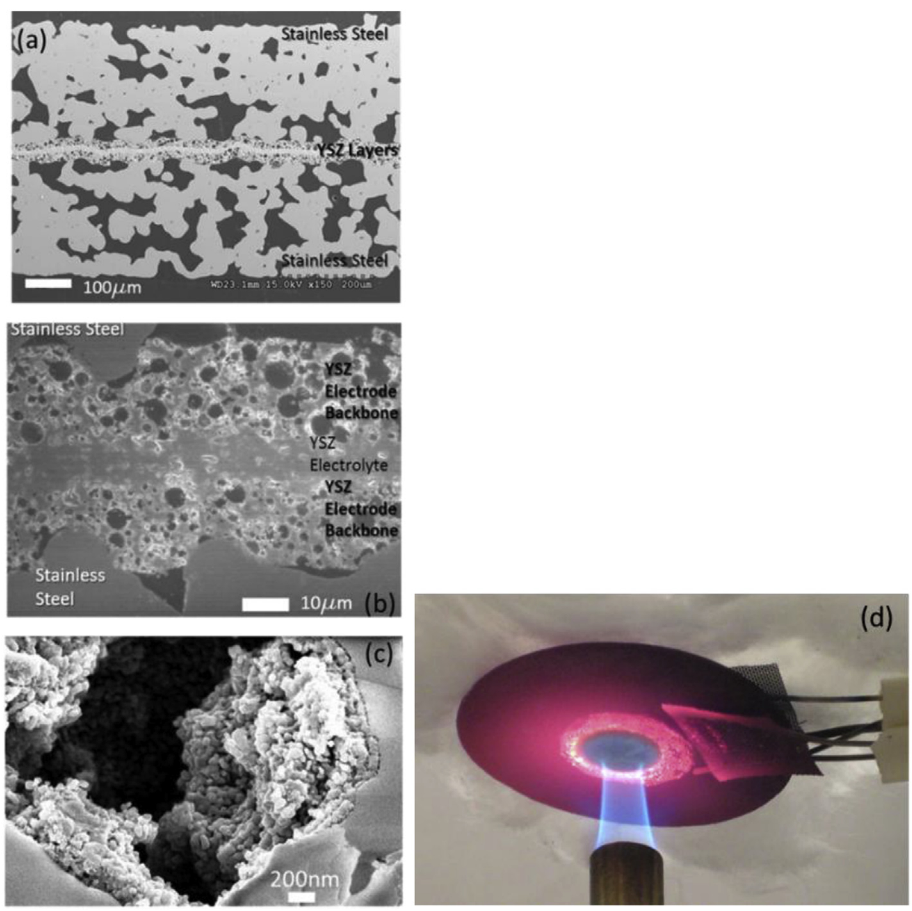

Fig. 1 – MS-SOFC and flame setup. SEM image of (a,b) polished cross section of MS-SOFC structure after sintering and before catalyst infiltration, and (c) cathode pore after infiltration of LSM nanoparticles. Approximate layer thicknesses are: metal support 250 μm, porous electrode 20 μm, and electrolyte 10 μm. (d) Picture of the anode side of the cell with flame impinging on the 1 cm^2 active area in the center of the cell. Reproduced from Refs. [33,34] with the permission of the publisher.