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Short communication

Micro-tubular flame-assisted fuel cells for micro-combined heat and power systems

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HIGHLIGHTS

- A novel furnace concept for micro-combined heat and power is proposed.
- Micro-tubular flame-assisted fuel cells are proposed and demonstrated.
- Significant power of ~430 mW cm^{-2} was achieved operating in fuel-rich exhaust.
- High fuel utilization (compared to direct flame fuel cells) was achieved 29.1%.

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ABSTRACT

Currently the role of fuel cells in future power generation is being examined, tested and discussed. However, implementing systems is more difficult because of sealing challenges, slow start-up and complex thermal management and fuel processing. A novel furnace system with a flame-assisted fuel cell is proposed that combines the thermal management and fuel processing systems by utilizing fuel-rich combustion. In addition, the flame-assisted fuel cell furnace is a micro-combined heat and power system, which can produce electricity for homes or businesses, providing resilience during power disruption while still providing heat. A micro-tubular solid oxide fuel cell achieves a significant performance of 430 mW cm^{-2} operating in a model fuel-rich exhaust stream.

1. Introduction

Heating systems including furnaces, hot water heaters and boilers are all based on combustion and heat exchanger systems that allow the chemical energy of a fuel, such as natural gas or propane, to be converted into heat. While these systems have become very efficient, there is an opportunity to utilize this same technology for power generation which will transform these heating devices into Combined Heat and Power (CHP) systems. Due to the low electricity demand in residential and small businesses, small scale CHP systems have been designated micro-CHP systems [1]. As these systems can operate on natural gas, propane, or wood they provide advantages compared to centrally distributed generation including resilience during power disruption, peak shaving and higher efficiency by avoiding transmission losses.

Despite the many options available for small scale power generation, Solid Oxide Fuel Cells (SOFCs) provide significant advantages for micro-CHP systems compared to their Internal Combustion Engine-based competitors because they are more-efficient, quieter, less polluting, and lacking moving parts, are potentially more reliable. Unfortunately, SOFC systems require complex fuel processing (due to a lack of a hydrogen infrastructure) and thermal management subsystems in order to operate at high temperatures (800–1000 °C) for long periods of time. The fuel processing subsystem reforms readily available hydrocarbons, like methane and propane, into hydrogen and carbon monoxide (syngas) that can more readily be used directly in SOFCs. The thermal management subsystem brings the SOFC up to operating temperature and prevents thermal shock by maintaining the temperature during operation. A recent development that combines fuel processing and thermal management is the direct flame fuel cell (DFFC) in which a SOFC is placed in direct contact with a flame [2–5]. The flame acts as a partial oxidation reformer, reforming fuel

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to syngas and products of combustion, while operating on a wide variety of solid, liquid and gaseous fuels. In addition, the flame simultaneously provides heat for the SOFC operation and thus combines the thermal management and fuel reforming into a single combustion process. Due to the simplicity of the setup, DFFCs have advantages over the more traditional dual chamber SOFC (DC-SOFC) [6] and single chamber SOFC [7–10] including rapid start-up and no sealing requirement [4,5,11–19]. Unfortunately, many studies have also revealed DFFCs achieve low fuel utilization (<1%) which makes the heat to power ratio impractical and the electrical efficiency low [4,5,13].

Instead of operating in direct contact with a flame, SOFCs could achieve higher fuel utilization if they were integrated into the fuel-rich exhaust stream of conventional combustion devices, creating a flame-assisted fuel cell (FFC). Specially, a SOFC can be integrated into a furnace, boiler or hot water heater exhaust in order to create a micro-CHP system that can potentially move the building off-grid. Fig. 1 shows one example of a proposed residential size flame-assisted fuel cell furnace for micro-CHP (FFF). This is one example of how FFCs can be used to create a micro-CHP system. Natural gas is fed through the gas line to the in-shot burner where the fuel is partially combusted. The fuel-rich exhaust moves through the tubular SOFCs generating power and heat. Any remaining fuel is mixed with a secondary dilution air stream to ensure complete combustion occurs prior to entering the flue. The exhaust gases then move through the flue and exchange heat with the external air stream which is used to heat the building. This novel furnace concept allows fuel-rich exhaust to generate power for the building. The electricity generated has immediate use in powering the furnace blower, running a refrigerator or being stored for later use.

The feasibility of the FFF concept was assessed in this study by first investigating the exhaust composition of the fuel-rich combustion of methane gas, which is the primary constituent of natural gas. The electrochemical behavior of a micro-tubular SOFC (mT-SOFC) [20–24] operating in a gas stream with the same composition and temperature as the combustion exhaust was analyzed. The mT-SOFC power curve, OCV and polarization were determined while operating in a model exhaust stream.

2. Experimental

2.1. Combustion characterization

Fig. 2 is a schematic of the combustion characterization chamber. Methane was chosen as the fuel for the mT-SOFC. The flow rate of methane was fixed at 10 L min^{-1} with the air flow rate varying in order to obtain the proper equivalence ratio. The equivalence ratio (ϕ) is defined as,

$$\Phi = \frac{n_{fuel}/n_{air}}{n^S_{fuel}/n^S_{air}}$$

where n_{fuel} and n_{air} are the molar flow rates of fuel and air respectively. Similarly, n^s_{fuel} and n^s_{air} are the molar flow rates of fuel and air for a stoichiometric reaction. Thus, an equivalence ratio of 1 represents a stoichiometric reaction and equivalence ratios greater than 1 are fuel-rich. The flow rate of methane and air was regulated by mass flow controllers and LabView software. A syringe was used to capture the combustion exhaust and direct it into a gas chromatograph (GC) for analysis. K-type thermocouples were used to measure the flame and the exhaust temperatures in the combustion apparatus. For the fuel-rich combustion of methane studied in this work, the exhaust composition is given by the following equation,

$$\Phi \cdot CH_4 + 2 \cdot (O_2 + 3.76 \cdot N_2) \rightarrow a \cdot H_2 + b \cdot CO + c \cdot CO_2 + d \cdot H_2O + e \cdot N_2$$

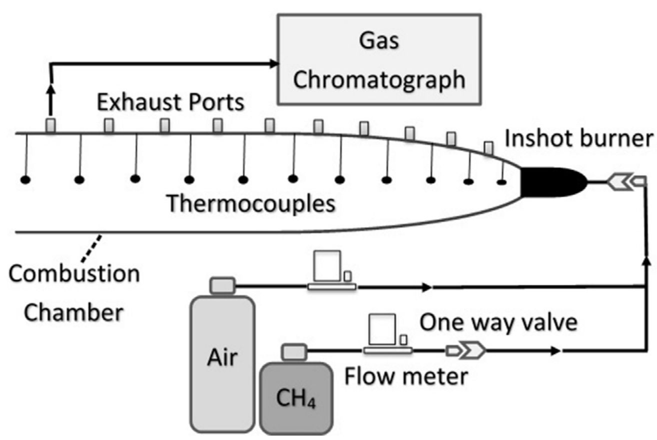

Fig. 2. Combustion characterization apparatus.

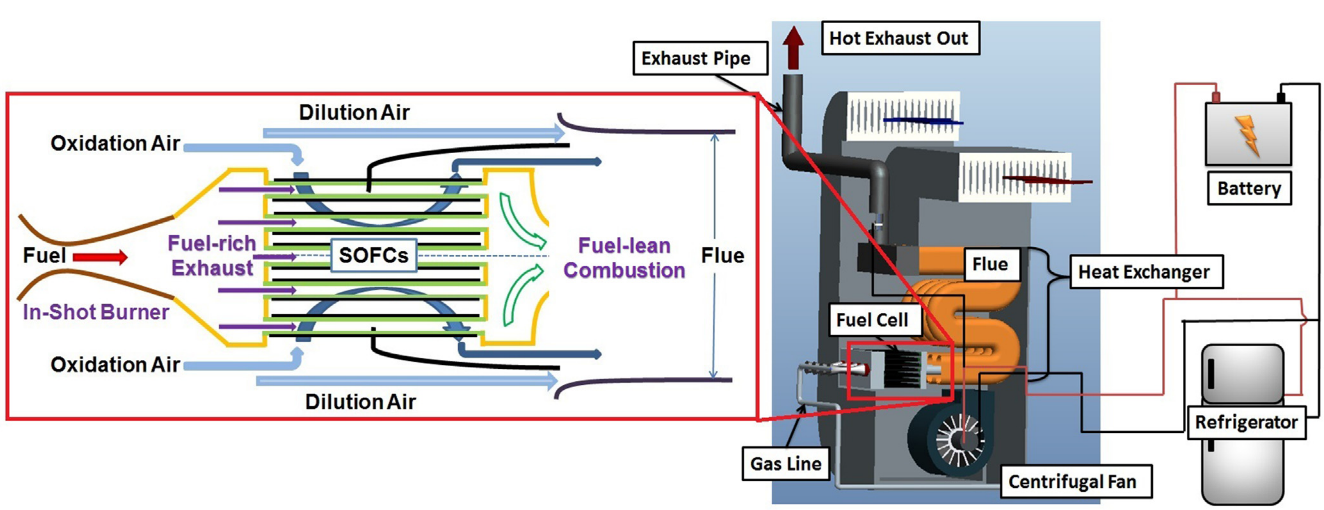

Fig. 1. Residential size flame-assisted fuel cell furnace for micro-CHP (FFF) concept.