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Rich-burn, flame-assisted fuel cell, quick-mix, lean-burn (RFQL) combustor and power generation

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HIGHLIGHTS

- Novel rich-burn, flame-assisted fuel cell, quick-mix, lean-burn combustor proposed.
- An optimal fuel-lean equivalence ratio of 0.8 is observed for peak power density.
- Richer fuel-rich equivalence ratios increase the fuel cell power density and OCV.
- Flame-assisted fuel cell electrical efficiency improved from 0.144% to 0.358%.

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ABSTRACT

Micro-tubular flame-assisted fuel cells (mT-FFC) were recently proposed as a modified version of the direct flame fuel cell (DFFC) operating in a dual chamber configuration. In this work, a rich-burn, quick-mix, lean-burn (RQL) combustor is combined with a micro-tubular solid oxide fuel cell (mT-SOFC) stack to create a rich-burn, flame-assisted fuel cell, quick-mix, lean-burn (RFQL) combustor and power generation system. The system is tested for rapid startup and achieves peak power densities after only 35 min of testing. The mT-FFC power density and voltage are affected by changes in the fuel-lean and fuel-rich combustion equivalence ratio. Optimal mT-FFC performance favors high fuel-rich equivalence ratios and a fuel-lean combustion equivalence ratio around 0.80. The electrical efficiency increases by 150% by using an intermediate temperature cathode material and improving the insulation. The RFQL combustor and power generation system achieves rapid startup, a simplified balance of plant and may have applications for reduced NO_x formation and combined heat and power.

1. Introduction

Solid oxide fuel cells (SOFCs) are solid-state, electrochemical energy conversion devices that have the potential for high efficiency and high fuel flexibility, but in general have suffered from slow startup and limited on/off and thermal cycling [1]. Thermal cycling is more of a challenge in the Dual Chamber (DC-SOFC) [2,3] configuration, which prompted the Single Chamber (SC-SOFC) [4–6] and the Direct Flame Fuel Cell (DFFC) configurations [7]. DFFCs are SOFCs operating directly in a flame in a simple, no-chamber setup [7–30]. The advantages of direct operation in a flame with no chamber include rapid startup, rapid thermal cycling, high fuel flexibility, and simplifications to the thermal management and reforming systems [31]. Unfortunately, thermal gradients across the cell resulting from direct contact with flame, low power density and low electrical efficiency have been major challenges for DFFCs to date [19,22,32]. Despite the potential for improving rapid startup and cycling, DFFCs are still being investigated for improvements in these areas.

A recent change to the original DFFC occurred with the proposal of operating a micro-tubular SOFC (mT-SOFC) in a dual chamber configuration directly in the combustion exhaust, termed a micro-Tubular Flame-assisted Fuel Cell (mT-FFC) [31–34]. The dual chamber configuration changes the typical partially premixed combustion setup of the DFFC to a premixed system with better control over the final combustion equivalence ratio and exhaust composition [31]. The premixed combustion exhaust composition has been characterized for methane and propane fuels in previous studies and FFC performance based on a model combustion exhaust has been conducted [31,33,35]. A micro combined heat and power system design has been proposed for this technology [32,36]. However, the dual chamber configuration means that additional fuel remains after passing through the fuel cell because 100% fuel utilization is not possible as a result of Nernstian losses. To overcome this a second, fuel-lean combustion in the fuel cell downstream is necessary. To date only the first-stage combustion and fuel cell

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operation in a model exhaust have been investigated, but a working system using this setup has not been developed.

The notion of a first-stage, fuel-rich combustion followed by a second-stage, fuel-lean combustion is an old combustor technology typically utilized to lower NO_x emissions from gas turbines with applications like jet engines [37–39]. The first-stage, fuel-rich combustion occurs at equivalence ratios above 1 which reduces the flame temperature and thereby reduces 'thermal NO_x' formation through the Zeldovich mechanism [40]. Reduction in 'fuel NO_x', or the oxidation of chemically bound nitrogen compounds in the fuel, has also been observed for two-stage combustion [40]. A premixed oxygen-deficient combustion, i.e. fuel-rich, leads to fuel bound nitrogen conversion to N_2 instead of complete conversion to NO which has been observed in oxygen-rich, i.e. fuel-lean, conditions [41,42]. The remaining fuel is then oxidized in a second-stage, fuel-lean combustor, but it requires a quick mixing of the oxidant stream in order to eliminate local high temperature regions and prevent further thermal NO_x formation [42]. As a result, this technology is often referred to as a Rich-burn, Quick-mix, Lean-burn (RQL) combustor, Rich-quench-lean (RQL) combustor [37,39,43,44] or two-stage combustor [40].

In this work, a new kind of two-stage RQL combustor is proposed. A first-stage, fuel-rich combustion is used to generate syngas in the exhaust stream. The exhaust then passes through SOFCs for conversion of the syngas to electrochemical power and thermal energy. Any remaining fuel existing in the fuel cell exhaust is mixed with an oxidant stream and a second-stage, fuel-lean combustion occurs. The first-stage, fuel-rich combustion provides thermal energy for the SOFC operation along with syngas while additional heat can be recovered from this stage and from the second-stage, fuel-lean combustion. This technology is denoted a Rich-burn, Flame-assisted fuel cell, Quick-mix, Lean-burn (RFQL) combustor. Fig. 1 shows one embodiment of the technology with a mT-SOFC stack arranged in a circle following the fuel-rich combustion chamber. This RFQL configuration operating on methane fuel is developed and investigated here.

2. Experimental setup

2.1. Combustor development and characterization

A RFQL combustor like the one shown in Fig. 1 was developed. A spark ignitor is used for ignition of the fuel/air mixture in the fuel-rich combustion chamber. K-type thermocouples are placed at different points of the fuel-rich and fuel-lean combustion chambers as shown in Fig. 2b. A flame arrestor is placed in the tubing before entering the RFQL combustor in order to prevent flashback. Methane and air are regulated at different fuel/air equivalence ratios using mass flow controllers. For the fuel-rich combustion chamber, the equivalence ratio is regulated between 1.05 and 1.40. The methane flow rate is fixed while the air flow rate is adjusted to achieve the desired equivalence ratio. Different flow rates of methane are also investigated ranging from 1.0 to 2.4 L min^{-1}. The equivalence ratio (Ø) is defined in Eq. (1) below. Here n_{fuel} and n_{air} are the molar flow rates of fuel and air, respectively; and n^S_{fuel} and n^S_{air} are the molar flow rates required for stoichiometric combustion of fuel and air, respectively.

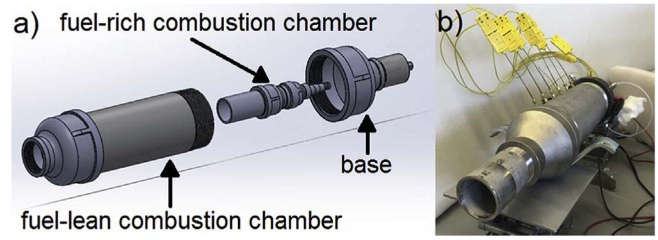

Fig. 2. a) Exploded view of the RFQL combustor CAD model showing the base with fuel-rich combustion chamber and fuel-lean combustion chamber and **b)** RFQL combustor assembled.

$$\varnothing = \frac{n_{fuel}/n_{air}}{n^S_{fuel}/n^S_{air}} \tag{1}$$

For fuel-rich combustion of methane and air, the following general reaction (2) occurs in the fuel-rich combustion chamber. Here a, b, c, and d are the mole fractions of the products of combustion. While the concentration of the products of combustion can vary significantly with the equivalence ratio (Ø), the species shown in Eq. (2) are the primary species observed in previous work [31,32] for the equivalence ratios investigated in this study.

$$\varnothing CH_4 + 2(O_2 + 3.76N_2) \rightarrow aCO + bCO_2 + cH_2 + dH_2O + 2(3.76)N_2 \tag{2}$$

For the second-stage, fuel-lean combustion, a mass flow controller is used to regulate the air flow. Four ports allow the air flow to be distributed evenly around the chamber. The air then passes over the outside of the fuel-rich combustion chamber for preheating. After preheating, the air passes over the SOFC stack for electrochemical reduction of the oxygen at the cathode. Any remaining fuel autoignites at the SOFC outlet for the second stage, fuel-lean combustion. The following reaction (3) occurs at the SOFC outlet.

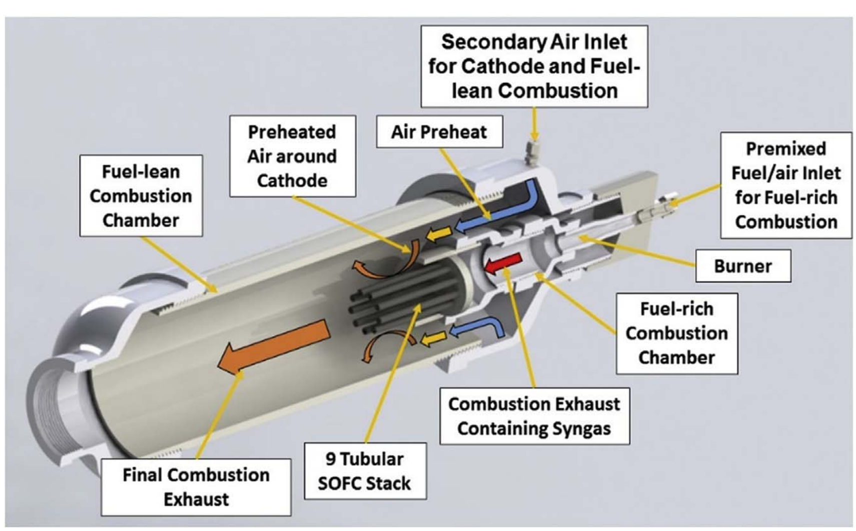

Fig. 1. One embodiment of the RFQL combustor with 9 mT-FFC stack.