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In-ground operation of Geothermic Fuel Cells for unconventional oil and gas recovery

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HIGHLIGHTS

- Novel CHP application of SOFC technology in unconventional oil and gas processing.
- Operation and performance of the world's first Geothermic Fuel Cell are described.
- Nine-stack GFC assembly is installed within the earth and operated for 600 h.
- CHP efficiency of 55% and heat flux 3.2 kW m^{-1} to the geology is achieved.

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ABSTRACT

This paper presents operating and performance characteristics of a nine-stack solid-oxide fuel cell combined-heat-and-power system. Integrated with a natural-gas fuel processor, air compressor, reactant-gas preheater, and diagnostics and control equipment, the system is designed for use in unconventional oil-and-gas processing. Termed a “Geothermic Fuel Cell” (GFC), the heat liberated by the fuel cell during electricity generation is harnessed to process oil shale into high-quality crude oil and natural gas. The 1.5-kW_e SOFC stacks are packaged within three-stack GFC modules. Three GFC modules are mechanically and electrically coupled to a reactant-gas preheater and installed within the earth. During operation, significant heat is conducted from the Geothermic Fuel Cell to the surrounding geology. The complete system was continuously operated on hydrogen and natural-gas fuels for ~600 h. A quasi-steady operating point was established to favor heat generation (29.1 kW_{th}) over electricity production (4.4 kW_e). Thermodynamic analysis reveals a combined-heat-and-power efficiency of 55% at this condition. Heat flux to the geology averaged 3.2 kW m^{-1} across the 9-m length of the Geothermic Fuel Cell-preheater assembly. System performance is reviewed; some suggestions for improvement are proposed.

1. Introduction

This paper presents a pilot-scale demonstration of a novel combined-heat-and-power application of solid-oxide fuel cell (SOFC) technology. The heat generated by operating SOFCs while generating electricity is harnessed to process oil shale into oil and natural gas. This “Geothermic Fuel Cell” concept is shown in Fig. 1. Solid-oxide fuel cells are placed hundreds of meters below the earth's surface within the oil-shale geology and continuously operated over a period of years. The thermal energy released during fuel-cell operation is harnessed to heat the surrounding oil shale to temperatures near 400 °C. At these temperatures, the kerogen trapped within the oil shale is retorted to form liquid oil and natural gas. Once formed, the resources are withdrawn from the formation using conventional “collector” wells. The natural gas can be used to fuel the Geothermic Fuel Cells. Three valuable products are generated: electricity, natural gas, and most-importantly oil [1].

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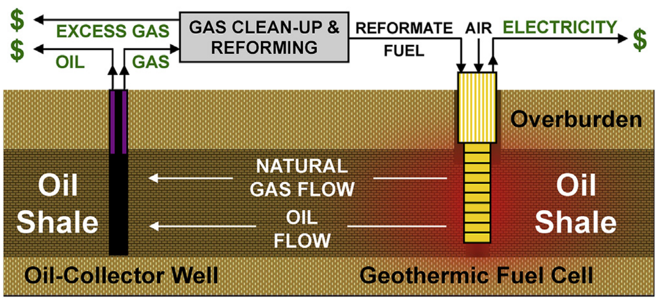

Fig. 1. Illustration of the Geothermic Fuel Cell concept, solid-oxide fuel cells provide the thermal energy to heat the oil shale formation.

The demonstration presented in this paper involves a near-surface installation of nine (9) 1.5-kW$_e$ fuel cell stacks into a clay formation at the Colorado School of Mines campus. Fueled by municipal natural gas, this Geothermic Fuel Cell is integrated with a natural-gas fuel processor, a reactive-gas preheater, and ancillary balance-of-plant and diagnostic components at an outdoor test site. The Geothermic Fuel Cell was continuously operated within the earth for a period of 25 days. This paper presents the results of this demonstration.

The U.S. Geological Survey estimates that over four trillion barrels of oil are trapped in the Piceance Basin of northwestern Colorado, the Uinta Basin of northeastern Utah, and the Greater Green River Basin of southwestern Wyoming [2,3]. In contrast to liquid shale oil (or "tight oil") trapped within porous geology [4], oil shale is a sedimentary rock that contains organic matter called kerogen [5]. When pyrolysed to ~350 °C [6], this kerogen decomposes into a mixture of oil, hydrocarbon gas and carbon-rich shale coke [7]. These oil-rich kerogen beds are buried below 250–600 m (800–1900 ft) of overburden, and can extend over 900 m (3000 ft) below the surface at the center of the basins.

The processing of oil shale into oil is well established [8]. Traditionally, the shale rock is mined from the earth and then retorted above ground. Significant oil-shale retorts have been in operation for decades in Estonia, China, Russia, and other sites. Conventional oil-shale processing is not cost competitive with Middle East sources. Environmental impacts – surface disturbance, water requirements, waste management – also present significant concerns [9]. Despite the enormity of this resource, its impact on the world energy portfolio remains modest [8].

Developers are turning to in-situ oil-shale processing to address these cost and environmental challenges. During in-situ processing, the oil-shale resource is retorted directly within the formation; this eliminates mining processes and minimizes surface operations [10]. Studies also show that in-situ processing leads to a significant increase in the energy yield, as greater volumes of oil shale can be processed at a time [11].

In-situ oil-shale processing is being pursued through a number of novel technologies, including:

- The "In-Situ Conversion Process" (ICP) led by Royal Dutch Shell; resistive heaters are inserted within the formation and driven with electric current to supply heat to the oil shale [7];
- The "Electrofrac Process" led by Exxon-Mobil; hydraulic fractures created in the formation are filled with an electrically conductive material to form resistive heating elements that are then driven with electric current to heat the oil shale [12];
- The "Volumetric Heating" method developed by Illinois Institute of Technology; radio waves generated by electrode arrays heat the formation [13];
- The "In-Situ Vapor Extraction Technology" pursued by Mountain West Energy; methane gas is heated above ground and injected into the oil-shale formation. A similar process is being developed by Chevron with carbon dioxide serving as the working fluid [14].

Geothermic Fuel Cells differ from these approaches in that electricity is generated throughout in-situ processing. This presents a unique Combined Heat and Power (CHP) application. In previous work, SOFC systems achieved CHP efficiencies approaching 85% [15–20]. Unlike most CHP applications, in-situ oil-shale processing places higher value on down-hole thermal-energy release, at the expense of electricity generation. Addressing such operational tradeoffs and learning of the engineering challenges associated with underground SOFC operation motivate the current study.

2. Experiment

In this demonstration, a Geothermic Fuel Cell assembly was installed in the earth and continuously operated for ~600 h. The GFC was fueled with natural gas that was passed through a fuel processor and converted into syngas. An extensive data set was acquired and used to quantify important performance metrics.

2.1. Geothermic Fuel Cell modules

A schematic of a single Geothermic Fuel Cell module is shown in Fig. 2. This assembly is centered on three 1.5-kW$_e$ solid-oxide fuel cell stacks that are packaged and distributed within a cylindrical stainless steel housing. The housing is approximately 0.3 m (1 ft) in diameter and 1.8 m (6 ft) in height. Reactants are fed to the stacks in a parallel arrangement, while the stacks are connected in electrical series.

During operation, the fuel and air reactants fed to the stacks are electrochemically converted to products and electricity.

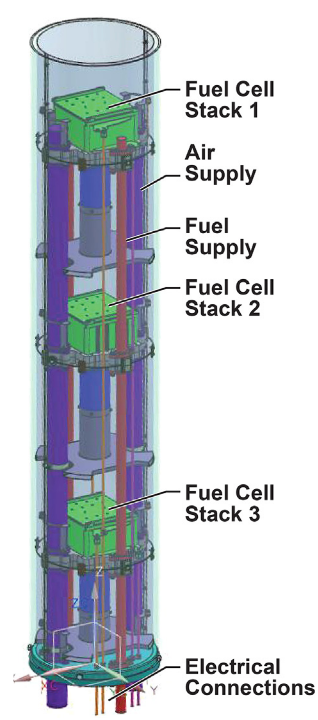

Fig. 2. Schematic of a single Geothermic Fuel Cell module. Three such modules were joined and placed within the earth as part of this demonstration.