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Original Research Article

Performance of a catalytic partial oxidation reformer for forward operating bases

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ABSTRACT

A forward operating base tends to have limited access to a power grid in addition to unique operating constraints. In order to meet its power requirements, a system that is compact and easy to operate is desirable. A catalytic partial oxidation (CPOX) reformer coupled with a generator offers compactness and ease of operation along with fuel flexibility. A 1 kW CPOX system was tested as part of a microgrid based on the Missouri University of Science and Technology microgrid. The system was made to follow a number of input current waveforms to simulate real-world loads using a programmable DC load. The system was demonstrated good load-following capabilities with the maximum average deviation for any given test not exceeding 30.1 W. This deviation increased as the power demand increased. The performance of the generator was found to be independent of the sulfur content of the fuel. The overall efficiency of the system was found to be 5–10%. Deposition of coke and unsteadiness in the generator were found to be issues. Solutions were proposed.

Introduction

A forward operating base (FOB) tends to be located in regions with no access to a power grid. As such, all the electricity needed to power communications, electronics, heating, lighting, and water purification must be generated on site, usually through the use of portable generators that are run on diesel [14]. In fact, half the fuel used on FOBs is to produce electricity from generators [8]. A diesel generator can provide a steady, portable electricity supply as an auxiliary power unit (APU) in military applications. However, proper utilization is an issue and the availability of diesel is a limiting factor. Growth of technology is often accompanied by an increase in fuel consumption. All this makes the availability of fuel a critical factor in the operation of FOBs. Fuel transportation is a dangerous and difficult operation for the military as fuel must often be transported for long distances over rough terrain and through hostile territory. Fuel convoys are usually guarded by soldiers and are a major target for the enemy. Attacks on fuel convoys have resulted in heavy casualties to troops [16]. The risks involved in fuel transportation caused drivers in Pakistan to double the price of transporting fuel into Afghanistan [12]. Moreover, an increase in fuel consumption would result in an increase in casualties to troops [7]. These factors have combined to drive up the price of fuel. The cost of fueling a military vehicle in 2003 was $600 per gallon in Afghanistan and $150 per gallon in Iraq [2].

Energy efficiency and proper utilization are important steps towards reducing fuel consumption. Estimates of fuel consumption at FOBs range from 1.0 to 5.6 gallons/day/soldier and estimates of average or continuous electricity demand at FOBs range from 0.5 to 3.5 kW/soldier [6]. One of the main problems with existing methods of generating electricity at FOBs has to do with the utilization of generators. In most cases, the existing capacity exceeds demand and the generators are underutilized. For instance, at Camp Leatherneck, the electricity demand is 5 MW, but the installed capacity is 19 MW. The result is that 196 generators are run at 30% capacity to meet the requirements [6]. Internal combustions engines operate at maximum efficiency when fully loaded. This efficiency tends to decrease as the load decreases [11,15,13]. Distributing the sources of electricity generation using microgrids could address the problem of utilization.

A microgrid is a localized collection of equipment to generate, store, and utilize electricity, which is capable of operation independent of a larger macrogrid. Microgrids are a convenient way to facilitate distributed generation. Fuel cells, fuel reformers, solar panels, and wind turbines are connected to various different storage devices (batteries, ultracapacitors, etc.) in order to supply

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List of symbols

amp	ampere
atm	atmosphere
APU	auxiliary power unit
ATR	autothermal reformation
AWG	American wire gauge
CPOX	catalytic partial oxidation
D_{avg}	average deviation
DC	direct current
FOB	forward operating base
FREEDM	Future Renewable Electric Energy Delivery and Management
JP-8	jet propellant 8
NEMA	National Electrical Manufacturers Association
PCI	Precision Combustion, Inc.
P_d	power demanded by the DC load
PEM	proton exchange membrane
P_g	power produced by the generator
PI	proportional plus integral
PID	proportional plus integral plus derivative
ppm	parts per million
RPM	revolutions per minute
SMR	steam-methane reformation
ULS	ultralow-sulfur
W	watt
$	dollar (US)
Δt	time step
η	efficiency

power to various loads resulting in a system that can function as part of a larger macrogrid (interconnected mode) or by itself (islanded mode). In this study, the challenges typically associated with microgrids were circumvented by using a relatively simple set-up, thereby eliminating the need for an energy management system. The set-up used will be described in Section 3.

In order to meet the power requirements of FOBs, this study proposes a distributed generation approach using a microgrid. The power source is a multi-fuel reformer connected to a generator capable of load-following. The proposed configuration is compact, modular, and can operate on almost any locally available hydrocarbon fuel thereby overcoming the challenges mentioned above. Its compact size means it is easy for soldiers to transport and its modularity means scaling up to meet increased power requirements is as easy as adding more units to the microgrid. The main contribution of this study is demonstration of the load-following capability of the fuel reformer and its ability to operate as part of a standalone microgrid.

Reformation

Reformation is a chemical process used to convert low-octane fuels to high-octane fuels. There are a number of fuel reforming technologies available: steam-methane reformation (SMR), catalytic partial oxidation (CPOX), and autothermal reformation (ATR). CPOX is a method to convert hydrocarbons to hydrogen, which is present in syngas. Eq. (1) shows the reaction in which a hydrocarbon is partially oxidized.

$$C_mH_n + \frac{m}{2}O_2 \rightarrow mCO + \left(\frac{n}{2}\right)H_2 \tag{1}$$

Since the reaction is exothermic, no catalyst is required. However, a catalyst increases the hydrogen yield [5], which is the lower than SMR, and reduces the operating temperature to around 700 °C allowing commonly available materials such as steel to be used to fabricate reaction vessels [1]. CPOX allows more compact systems than SMR since no external heat is required. Additionally, CPOX systems have a quick start-up and transients are relatively easy to control, implying good load-following capabilities.

For APU applications, CPOX systems seem to be attractive since they are compact and don't require external heat; no igniter is needed. They have a quick start-up and are relatively easy to control. The hydrogen yield is the lowest, but may not be an issue for generator applications. Heat removal may not be an issue for a small system, on the order of 1 kW. The CPOX reformer used in this study was developed by Precision Combustion, Inc. (PCI). In addition to being highly portable and having all the other benefits of CPOX reformers mentioned previously, it is a multi-fuel reformer with a high efficiency of 85%. Typical efficiencies for comparable systems range from 70% to 80%.

This high efficiency is due to the innovative catalyst support used. The heat and mass transfer coefficients of the catalyst depend on the boundary layer thickness. For a conventional long-channel honeycomb monolith, a fully developed boundary layer is present over a considerable length of the catalytic surface, limiting the rate of reactant transport to the active sites. This is avoided when short-channel-length catalytic screens are used. The Microlith substrate is a mesh-like structure coated with catalyst. It has high mass and heat transfer properties as well as high surface area. Use of catalyst substrates with high mass transfer rates, a high surface area, and a low pressure drop has a significant impact on reactor performance and size. PCI has developed a Microlith-based (trademarked by PCI) approach. The catalyst and reactor are based on PCI's patented Microlith technology. The Microlith substrate consists of a series of ultra-short-channel-length low thermal mass catalytically-coated metal meshes with very small channel diameters. The short channel length minimizes boundary layer build-up and results in remarkably high heat and mass transfer coefficients compared to other substrates (e.g. foams, monoliths, pellets). The substrate provides about three times higher geometric surface area over monoliths with equivalent volume and open frontal area. PCI's proprietary catalyst coatings, with high surface area wash-coats, allow for very low catalyst usage with rigorously demonstrated mechanical and performance durability [10]. The characteristics of the catalyst used for coatings in such applications by PCI are well documented [17,19].

A limiting factor while selecting fuels for a CPOX system is the sulfur content of the fuel. Sulfur tends to form inactive compounds on the surfaces of catalysts thereby reducing their effectiveness at catalyzing a reaction. Poisoning of the catalyst is generally avoided by using fuels with a low sulfur content (<15 ppm), which can be achieved by a desulfurization stage. It may be noted that CPOX systems using catalysts with a significantly higher sulfur tolerance (400 ppm–3000 ppm) have been developed [9,4]). The energy efficiency, however, tends to be lower than SMR due to problems with heat recovery. High-temperature studies have shown a reduction in the poisoning effect of sulfur [3]. However, high-temperature transients may cause catalyst degradation [18].

The primary aim of this study is to test the performance of a CPOX reformer as an APU for military microgrid applications. In particular, the load-following capability and the ability to cope