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Diesel-Fueled Solid Oxide Fuel Cell Auxiliary Power Units for Heavy-Duty Vehicles

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Abstract

This paper explores the potential of solid oxide fuel cells (SOFCs) as 3–10-kW auxiliary power units for trucks and military vehicles operating on diesel fuel. It discusses the requirements and specifications for such units, and the advantages, challenges, and development issues for SOFCs used in this application. Based on system design and analysis, such systems should achieve efficiencies approaching 40% (lower heating value), with a relatively simple system configuration. The major components of such a system are the fuel cell stack, a catalytic autothermal reformer, and a spent gas burner/air preheater. Building an SOFC-based auxiliary power unit is not straightforward, however, and the tasks needed to develop a 3–10-kW brassboard demonstration unit are outlined.

Introduction

Solid oxide fuel cells could find application on trucks and military vehicles as auxiliary power units (APUs) for operator quality-of-life and housekeeping needs (e.g., heating, air-conditioning, and on-board electronics) and for cargo needs (e.g., refrigeration). Historically, auxiliary power has been generated as parasitic power drawn from propulsion power or by continuous engine idling or lead-acid storage batteries (primarily for military vehicles) when propulsion power is not required. Diesel-fueled auxiliary power units (APUs) have been developed for trucks and military vehicles to improve fuel efficiency, reduce engine noise and emissions, reduce engine wear, and meet the increased demand for housekeeping power and quality-of-life features. Three major applications for APUs are (1) overnight units to reduce noise and emissions, thus addressing

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anti-idling bans, (2) full-time units to replace engine-mounted alternators and electrically driven components, and (3) units dedicated to cargo needs, such as refrigeration. Although APUs for trucks and military vehicles can reduce engine noise and emissions, as well as increase fuel efficiency, there is considerable room for improvement. Futhermore, APUs are bulky, and for military applications, they tend to be used on high-cost combat vehicles where the added cost can be more easily adsorbed. For certain military applications, lead-acid storage batteries are still used to provide auxiliary power when propulsion power is not required. Problems with lead-acid storage batteries include deep discharge, high cost, high maintenance, and the need to recharge the batteries.

New technologies that offer the potential for improvements in fuel economy and reliability, as well as reduction in emissions and maintenance requirements, are required. Fuel cells, which are essentially solid-state devices with few moving parts, offer these benefits.

Among the various types of fuel cells, the polymer electrolyte cells (PEFCs) have been the unanimous choice of the automotive companies for prime power in vehicles. The main reasons are the ability to startup at ambient temperature start-up capability and the mechanical robustness. As auxiliary power units, however, the PEFCs may not be the optimal choice, because the cost of the fuel processing train does not scale down well to the considerably smaller electrical capacity, and because the prevalent fuel in trucks and military vehicles is diesel, which is much harder to process than gasoline. Solid oxide fuel cells can operate on mixtures of hydrogen and carbon monoxide, permitting the fuel processor to be simple and inexpensive. Unlike the prime power application with its frequent start-ups and shut-downs, an auxiliary power system may operate more continuously. The longer start-up time of the SOFC compared with the PEFC may weigh less heavily. In this paper, we examine a conceptual design for an APU built around an SOFC to explore the system tradeoffs and heat and water management issues.

Solid Oxide Fuel Cells as APUs

An APU of ~5 kWe net power could be developed an SOFC system operating on diesel or similar on-board fuel. A catalytic autothermal reformer (c-ATR) can be used to convert the fuel to the fuel gas for the fuel cell. Such an APU offers distinct advantages over an APU based on, for example, a diesel engine/generator set. Along with these advantages, however, there are developmental challenges and issues as well.

Advantages

The major components of this power generator (fuel processor, fuel cell stack, and air preheater) are solid state, while the total system has only a few moving parts (air blowers, fuel, and water pumps). Using the c-ATR to convert the on-board fuel to a gas mixture of H_2, CO, CO_2, and N_2, with small amounts of CH_4 and possibly other species, the SOFC system can operate with the conventional logistics fuel(s) with minimal fuel processing. This is because the SOFC can use CO as a fuel, either by direct electrochemical oxidation of the CO, or by the conversion of the CO to H_2 and CO_2 by reaction with water vapor (the water-gas shift reaction). These processes within the anode of an SOFC have been modeled (1), as well as demonstrated experimentally on aviation fuel, JP-8 (2).

Any methane or other light hydrocarbons or alcohols produced by the autothermal reforming reactions would be converted to hydrogen by reaction with water vapor within the anode flow field of the SOFC, making use of the stack waste heat for the endothermic steam-reforming process. The nickel used as the anode electrocatalyst is an active steam-reforming catalyst, and the fuel cell temperature, approximately 800°C, is high enough to obtain high reaction rates. Further, the required water vapor is generated within the anode flow as a product of the cell reaction.

By appropriate design and operation of the c-ATR, one can vary the level of methane in the reformate to permit matching of the endothermic energy requirement of the steam-reforming reaction with the exothermic energy (waste heat) produced by the electrochemical cell reaction. Typically, this waste heat is removed from the stack by using excess air as the cathode flow, which leads to significant power consumption at the air blower (3). Using part of this waste heat for the steam reforming of CH_4 and other light hydrocarbons reduces the air flow requirement for cooling the stack, with a concomitant reduction in parasitic power consumption in the fuel cell system. Further, since complete conversion of CH_4 is not required in the c-ATR, the amount of water fed to the c-ATR can be reduced This reduction, in turn, improves the overall system efficiency.

The SOFC's operating temperature of ~800°C is close to the 750–850°C operating temperature of a c-ATR for converting diesel and other hydrocarbon fuels to a mixture of H_2, CO, CO_2, N_2, H_2O, and other species (4). This feature permits close coupling of the reformer with the fuel cell, offering excellent potential for thermal integration of the two key chemical and electrochemical components in the APU system for efficient power generation. In other reformer-fuel cell combinations, the operating temperatures of the reformer and the fuel cell are very different (e.g., 200°C for the phosphoric acid fuel cell used in demonstration transit buses, and 80°C for the polymer electrolyte fuel cell used in automotive and transit bus demonstrations). A large difference between the reformer and fuel cell operating temperatures requires significant heat exchange components, leading to thermodynamic and operating inefficiencies.

The SOFC-based APUs will have very low emissions, certainly as compared to an engine/generator-based APU. The pollutant emissions from the fuel cell APUs are governed by the catalytic burner in the system, which combines the anode exhaust with the cathode exhaust. The hydrogen and other fuel gases in the anode exhaust are completely oxidized to H_2O and CO_2 by the excess oxygen available in the cathode exhaust, reducing the emissions of CO and unburned hydrocarbons to trace levels. Particulate emissions are essentially eliminated. Further, by appropriate system design, the burner temperature can be limited to ~800°C so that NO_x levels are $\leq$100 ppm by volume in the APU exhaust.

The SOFC-based APUs are expected to reach system level efficiencies of $\geq$30%, based on the lower heating value of the on-board fuel. This holds even for relatively simple system configurations, such as the one shown in Fig. 1. In this system, the fuel, preheated air, and steam are fed to the c-ATR, from which the reformate flows directly to the SOFC. A major fraction of the preheated air is also fed to the SOFC. Water needed for the c-ATR is condensed out of the anode exhaust from the SOFC. Hydrogen and CO in the "dried" anode exhaust are burned in the catalytic burner using the cathode exhaust, and the resulting hot gas is used to preheat the process air as well as to generate steam for the c-ATR before being vented from the system. The schematic diagram shown in Fig. 1 is not meant to be representative of the actual hardware configuration. For example, the catalytic burner and the air preheater shown as two separate process components may be configured as one integrated piece of hardware in practice. With improved thermal and process integration, efficiencies approaching 40% could be achievable. This would come, however, at the expense of added system complexity.

Challenges

Although the combination of the c-ATR and the SOFC operating at similar temperatures has the potential of achieving high thermodynamic efficiencies, attaining that potential requires the design of system configurations that maximize thermal integration by minimizing irreversibilities, both in the heat exchange components and in the fuel cell itself.

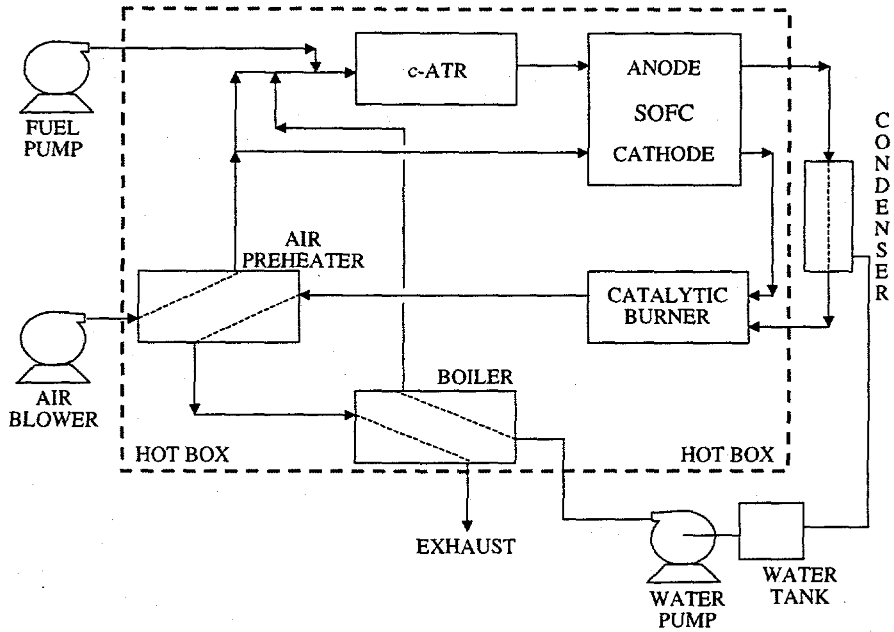

Fig. 1. Schematic system diagram for an SOFC auxiliary power unit.

In Fig. 1, for example, the anode exhaust gas is cooled from ~800°C to ~60°C to condense and recover the water needed at the reformer. This water is then vaporized in the boiler to generate the steam feed to the reformer. The heat removed at the condenser is not effectively used to preheat the air and/or water fed to the c-ATR or the fuel cell and, therefore, the system efficiency is degraded. Due to the large temperature difference driving force available with this arrangement, however, the condenser can be considerably smaller than if it is placed at the system exhaust. One other practical advantage of the condenser placement in Fig. 1 is that the catalytic burner temperature is lower than it would be if the anode exhaust were not cooled, thereby decreasing the formation of NOx at the burner.

Thus, various tradeoffs in system configuration, component sizes and weights, and system packaging must be considered in order to minimize inefficiencies and heat losses. At the same time, complexity must be minimized to permit ease of control in normal operation.

As shown in Fig. 1, all of the high-temperature components of the system are placed inside an insulated thermal enclosure (indicated by a dashed line), referred to as the "hot box." Areas of concern include packaging these components, minimizing the sizes of the flow lines between the components, sealing, and thermal and electrical insulation.

To make such SOFC-based APUs viable, system startup protocols must be developed that consume the least amount of time and fuel before the APU can begin to deliver the power to the load. Also, the catalytic autothermal reforming process uses water to decrease the potential for coking and to permit operation at a lower temperature than would be feasible without water. For use in heavy-duty vehicles, the necessary water must be recovered from within the process. Effective approaches to doing so must be developed.

Development Issues

Several specific components must be developed for the SOFC-based APU for trucks and military vehicles. These include (a) a fuel, (b) planar fuel cell stacks of the requisite power ratings using diesel reformate, and (c) spent-gas burner/air pre-heater.

Several organizations in the U.S. (5) and elsewhere are developing autothermal fuel processors for use in transportation fuel cell systems. However, most of these projects are on reforming gasoline for PEFC systems. As such, a major part of these efforts is devoted to the conversion of CO to H_2 by the shift reaction, and final reduction of CO to trace levels by catalytic preferential oxidation or other means. For the SOFC-based APU, the CO conversion and cleanup are not required. The diesel (or other logistics) fuel, however, will require c-ATR designs and operating conditions different from those for a gasoline reformer. Specific issues to be addressed are: the need for minimizing or eliminating water/steam in the feed; operating temperatures compatible with those of the fuel cell; tolerance to sulfur at levels expected in the fuel; and size and packaging that permit a well-integrated reformer-fuel cell subsystem.

Planar fuel cell stacks offering $\geq$0.4 W/cm^2 have been designed and tested, but not yet at the ~5-kW power levels. As discussed later, a 5-kW stack could be smaller than a 20-cm cube in overall dimensions, with an active cell area of 1.25 m^2. However, specific issues related to stack design, operation on reformate, projected lifetimes, and physical and mechanical ruggedness must be addressed.

In principle, the catalytic burner can be effectively combined with the air preheater in a device similar to the fuel cell stack. Ceramic or metal-ceramic designs may be considered for this application, and prototype hardware must be developed. Finally, effective packaging concepts for the APU components, as well as system control protocols for startup, steady-state, and transient operation, must be developed.

System Design and Analysis of A SOFC-Based APU

Using Gctool (6), we have analyzed the APU shown schematically in Fig. 1 for operating conditions and efficiencies. As discussed above, the major components of this system are the fuel cell stack, the catalytic autothermal reformer, a catalytic burner for the spent fuel, and an air preheater for the cathode and reformer air. All of these components are housed in an insulated thermal enclosure. Additional significant components are a condenser for water recovery and a boiler to generate steam for feed to the c-ATR. Fuel and water pumps and an air blower make up the rest of the system components.

Table 1 summarizes the results from modeling a system operating on diesel fuel. For this simulation, diesel fuel was taken as a blend of 50% n-hexadecane, 20% n-propylcyclohexane, and 10% each of 1-hexadecene, n-butylbenzene, and naphthalene (molar composition). As shown in Table 1, the cathode air feed rate was set relatively high. This was done to limit the temperature rise from cathode inlet to cathode outlet to ~50°C and thereby minimize thermal stresses.

Table 1 shows that the overall energy conversion efficiency is 31% (based on the lower heating value of the fuel, LHV). However, this system design is rather conservative and has little thermal integration, other than the close coupling of the c-ATR with the SOFC. For example, with the c-ATR efficiency of 77% and the overall system efficiency of 31.1%, the balance-of-plant efficiency is ~72%.

This balance-of-plant efficiency, as well as the overall system efficiency, can be increased significantly by operational and design changes. For example, by reducing the airflow to one-half of the base case value and increasing the fuel utilization from 80% to 85%, the system-level efficiency can be increased to 34%. If the fuel utilization is increased to 90%, and the airflow is reduced to one-third of efficiency can be obtained by using the heat rejected at the anode condenser to provide some of the air preheat, by increasing the fuel and oxidant utilization, etc. Thus, it is clear that even the relatively simple system configuration can yield high operating efficiencies, although some of these efficiency gains would be at the expense of system simplicity and, perhaps, additional stresses in the ceramic stack components.

Table 1. Operating parameters for the base-case 5-kW SOFC system.

Fuel Cell Stack	
Cell voltage, V	0.750
Cell temperature, ^{o}C (average)	800
Cathode air feed rate, g/s	63
Anode fuel gas feed rate, g/s	3
Cell efficiency, %	56.2
Autothermal Reformer	
Fuel flow rate, g/s	0.35
Air feed rate, g/s	1.95
Water/steam feed rate, g/s	0.70
Steam-to-carbon, mole ratio	1.50
Reforming temperature, ^{o}C	760
Reformer efficiency, % (LHV)	77
Overall System	
Efficiency, % (LHV)	31.1

These analyses show that system efficiencies based on the net power production can approach or exceed 40%. However, the design and operating parameters influence the power density, size and weight (and cost), mechanical stresses, and operational control, in addition to system efficiency. Compromises must be made in designing the system for the heavy vehicle application. For example, the fuel cell stack is likely to be the most expensive component in this system, and obtaining the highest power density would minimize that cost. Although increasing the efficiency, high fuel utilization on reformate fuel would reduce the operating cell voltage, leading to lower power densities. On the other hand, the catalytic burner/air preheater is likely to be the largest component (in terms of weight and volume) in the system, other than the insulated hot box. The system-level power density may be increased by operating with high-temperature-difference driving forces, which would allow reduced size of the burner/preheater; however, the result would be an increase in the thermodynamic inefficiencies and reduced overall efficiency.

The SOFC stack itself can be rather compact. Kim et al. (7) have reported power densities of ~1.8 W/cm^2 for anode-supported single cells at 800°C at 0.5 V and ~1.0 W/cm^2 at 0.75 V (7). Assuming stack-level power densities of 0.4 W/cm^2 are achievable, a 5-kW SOFC would require an active area of 1.25 m^2. This could be obtained with 55 cells of 225-cm^2 active area each. With three cells per centimeter, the SOFC stack would approximate an 18-cm cube (assuming square cells), for a stack power density of 0.86 kW/L of total stack volume.

Sizes of the heat exchangers range from 0.09 m^2 active area for the anode condenser to 4–8 m^2 for the catalytic burner/air preheater (for the higher efficiency case). Decreasing the extent of air preheat would shrink the size of the air preheater, but there would be a small penalty in system efficiency.

Development of Brassboard Demonstration Unit

Planar SOFC stacks and other system components have been developed to the stage where it appears practical to develop a prototype 3–10-kW brassboard demonstration unit. Several issues still need to be addressed before this can be accomplished, as discussed above. It is possible, however, to delineate the tasks and steps that might be undertaken in pursuit of this objective. These include (i) a more detailed engineering design of the system that takes into account the various tradeoffs discussed above; (ii) fuel processor design for the specific logistics fuel and determination of its operating envelope, such as permissible air-to-fuel and water-to-fuel feed rates, air and water preheat temperatures, and reformate exit temperatures and compositions; (iii) design and development of planar SOFC stacks to generate ~5 kW; (iv) design and development of the catalytic burner/air preheater, including selection of low-cost materials for this component; and (v) analysis and resolution of system integration and control issues and protocols.

Discussion and Conclusion

The analysis shows that an SOFC-based APU would have few components and would occupy a volume of probably less than 100 liters, with the air preheater being the largest unit. The efficiency with diesel fuel, which has rather low hydrogen-to-carbon ratios and is difficult to reform, would still be close to 40% LHV.

Planar solid oxide fuel cells of 3-10k W capacity are available but have not yet demonstrated the high reliability and durability of tubular SOFCs. Autothermal reformers for diesel are also being tested in the specified size range. Air preheaters and condensers would have to be designed and tested for this application and would not be expected to represent major challenges. Building such systems is not straightforward, however, because critical unanswered questions are the thermal stress tolerance during start-up of a system with major ceramic components, and their toughness in a hostile environment. Considering how much effort has been spent on PEFC system development, and how relatively few resources have been allocated to addressing the critical issues for SOFCs, it would seem appropriate to seriously consider the SOFC technology for this application.

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