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THE RURAL AREA POWER PROGRAM DIESEL REFORMER EVALUATION

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Abstract

The Remote Area Power Program was created to evaluate the possibility of using PEM fuel cells with diesel reformers for residential power in remote areas. This technology was advertised as being clean, efficient, reliable, and cost-effective, and business plans were presented that showed major commercial deployment by 2001 or 2002. The industry also claimed that diesel reformers would be available in the near future, which would make this technology very attractive for remote areas like rural Alaska. Based on these claims, a technology validation program was started in the summer of 1998 to verify these claims.

The program has evaluated a total of five PEM fuel cell stacks, and diesel reformers from two sources. However, we have been unable to obtain an integrated reformer/fuel cell system from an industrial source, and are experiencing some difficulties with the small-scale diesel reformers delivered to the program. Furthermore, our work to date has been unable to verify some of the more attractive claims of this technology with hardware delivered to the program, including the efficiency and reliability necessary for successful commercial deployment.

Background

In order for PEM fuel cell systems to obtain a significant market, they must successfully compete with existing technologies, and prove significantly better than these technologies in some way. For the case of rural Alaska, the existing conventional technology is the Diesel Electric Generator (DEG). Current electrical generation costs in remote villages vary from 20 to 80 cents per kilowatt hour, indicating the possible presence of a profitable niche market for competing technologies.

The PEM fuel cell suppliers claimed that their systems would provide electricity at an efficiency of 40% net electrical (LHV), be reliable with a lifetime of 40,000 hours (5 years), and have a capital cost of about $3,500 per 5kW unit, where heat produced by the unit could be recovered for residential use. Furthermore, there were significant claims with regards to the environmental benefits, with some web sites claiming that the only emissions would be water vapor (how a hydrocarbon can be reformed without the production of CO_2 was not addressed). The goal of this program was to evaluate these claims, and to demonstrate this technology in the field.

Methods and Results

The first major goal of this program was to measure the thermodynamic efficiencies of the PEM systems. Since the efficiency depends on the system boundary, our choice of boundaries was to make this system as directly comparable to conventional technology as possible. We elected to use the same system boundary that Alaskan utilities use for evaluating the efficiency of their operation, i.e., the AC electrical energy out divided by the diesel fuel in (LHV).

A PEM fuel cell system requires three subsystems in order to meet the diesel in/AC out boundary: a reformer, to convert the hydrocarbon fuel into usable hydrogen, a PEM fuel cell stack to convert the hydrogen into DC electricity, and an inverter to convert the DC electricity in to AC usable by the residence. There are also significant balance-of-plant issues, including air supplies for both the reformer and the fuel cell stack, and water supplies for both the fuel cell and the reformer. These balance-of-plant needs require blowers and pumps, which act as parasitics on the system. In addition, if the unit is to be operated in a grid-independent mode, some of the energy must be stored in a battery bank, which reduces the overall system efficiency.

In order to make these measurements, several test benches were built, carefully calibrated, and used to evaluate the fuel cell performance. During the first two years of this program, the systems efficiencies were measured for five fuel cell stack systems operating on pure hydrogen. Our findings, which were consistent between stacks, indicated that current technology can deliver nearly 50% net electrical efficiency based on the LHV of hydrogen when the stacks are operated at 2.5 kW DC out. This is a system number for a stack operated at atmospheric pressure with a blower, and includes all parasitics and a hydrogen purge resulting in some fuel loss.

The program then moved on to the more difficult issue of the diesel reformer. It soon became apparent that there were some outstanding issues associated with reforming in general, and some issues very specific to the reforming of diesel and other heavy hydrocarbons. One important issue is simply that as reformers get smaller, the surface-to-volume increases, resulting in higher heat losses from the smaller devices. This, in turn, leads to problems in maintaining even temperature distributions in these small devices, which can lead to operational issues. Furthermore, the additional heat loss must result in a lower reformer efficiency, as compared with the efficiencies achievable in larger systems.

It also became apparent that there are many ways of defining an efficiency of a reformer. For catalyst evaluations, some sources report a fuel conversion rate as an efficiency, as this does indicate how well the catalyst is at converting a feed stock into hydrogen. However, for steam reforming, heat must be supplied to drive the exothermic reaction forward, and this heat must be supplied in one form or another from the incoming fuel. For this reason, we elected to use an efficiency based on the fuel value of the usable hydrogen delivered from the reformer to the fuel cell divided by the fuel value of the incoming fuel. Electrical parasitics required by the reformer also were measured, and subtracted from the electrical output of the fuel cell system.

The Northwest Power Steam Reformer

The first reformer evaluated was supplied to the program from Northwest Power Systems of Bend, Oregon (currently Idatech). Northwest Power is developing residential power systems based on methanol as a feedstock, and the kerosene/diesel reformer represented a first attempt to expand the fuel options used by their technology. This reformer was a steam reformer with a membrane to purify the hydrogen, with only small amounts of water vapor and methane as impurities. The high quality of this product gas has been verified by gas analysis, which indicated that there is less than 1ppm CO in the product gas.

The NPS steam reformer was successfully used in a demonstration, using desulfurized kerosene as a fuel, providing hydrogen to a 3kW fuel cell stack, which powered an inverter, and was used to run the laboratory lights during a public demonstration.

However, there were several drawbacks to the NPS diesel reformer. When the unit was operated in a self-sustained mode, the overall efficiency as defined above was at best about 35%. Measurement of the energy balance indicated that significant energy was lost through the combustion exhaust. Our runs with this unit were also frequently interrupted by coking events, which were explainable in part by control system problems. However, other issues were likely involved, and it was not clear that these issues could be addressed within the scope of this program.

The Autothermal Integrated System

There are two different technologies for PEM fuel cell systems operating on hydrocarbon fuels. The first, described above, is to create a reformer that provides pure hydrogen to a PEM stack designed to run on this gas. However, the purification of the reformer product gas is done using a membrane, and the membrane needs a significant partial pressure drop in order to work. But once the pure gas is provided, the PEM stack issues are much simpler, as the pure gas is much easier to handle in the stack.

The second alternative is to use a reformer that provides a hydrogen-rich gas stream to the fuel cell. This strategy is used in the phosphoric acid and solid oxide fuel cell systems, and has the advantage that the reformer can operate at near atmospheric pressure. However, PEM technology is significantly different than the other fuel cell technologies in that it is sensitive to much lower levels of CO in the gas stream, and so the clean-up stages must provide adequate removal of this CO from the product stream.

One of the major advantages of this scheme is that an autothermal reformer can be used, similar to those in other fuel cell systems, but with a more robust CO removal system. Autothermal reforming includes a partial oxidation reaction (POX) followed by a steam reforming reaction. Since the partial oxidation reaction is exothermic (it is a fuel-rich combustion reaction, which produces both hydrogen and heat) and the steam reforming reaction is endothermic, the net result is a reaction that produces a hydrogen-rich stream without heat transfer across a heat exchanger wall. A disadvantage of this system is that the gas that is fed to the fuel cell is not pure hydrogen, but rather a mixture of carbon dioxide, water vapor, methane, nitrogen, and hydrogen. Therefore the fuel cell anode sees a lower partial pressure of hydrogen, and produces a somewhat lower electrical potential than would a pure hydrogen fuel cell stack.

In order to test this system, the RAPP Program solicited bids for an integrated autothermal PEM system using diesel or kerosene. This bid was awarded to Dais Analytic, and required delivery of a diesel reformer by May 2000, and delivery of an integrated system suitable for residential power by August 2000. The diesel reformer to be delivered in May was part of an existing program between Argonne NL and Dais, and was to be first shipped there for preliminary evaluation before being sent to Alaska.

However, the shipment of the diesel reformer did not occur in May 2000, and by late August, some concern was raised. At this time, the DOE project officer decided that something needed to be done to motivate Dais, and arranged a training meeting at Dais in late August. Representatives from Sandia NL Livermore, Argonne, and the UAF Energy Center went to the Dais Analytic site in Woburn, MA for a week-long training session.

There were two significant things that did not occur during the week. The first was that the reformer did not run, due largely to the non-performance of an auxiliary burner. The second item was that the management of Dais-Analytic failed to provide a suitable revised timetable for delivery of the integrated system within the specifications of the contract, and instead tried to renegotiate the terms and conditions of the agreement, for a significantly increased amount. These discussions eventually ended with a termination of the contract for the integrated system for non-performance of the contract.

The Dais Analytic diesel reformer was eventually delivered to Argonne NL on October 31, 2000, precisely one year after the original date specified in the contract with Argonne. The unit was shipped to the UAF Energy Center, and arrived shortly before the end of the year.

It quickly became evident that the Dais diesel reformer is a laboratory device, and a significant distance away from being a commercially viable unit. The performance of the auxiliary burner continued to be an issue for two reasons: the low fuel flow rate caused problems with the nozzle in the burner, and the glow plugs used to ignite the fuel-air mixture frequently failed. The second issue led to some additional problems, when a short in the glow plug led to 120 volt current jumping a relay and damaging the electronics in the control board, causing a delay in the testing program. Eventually, however, these issues were solved at least to the level where the reformer could be operated for experiments.

In spite of the difficulties experienced, the Dais diesel reformer proved to perform well in the laboratory. The control system supplied with the unit functioned quite well, as start-up and operation required very minimal operator interaction. The materials used in the construction of the reformer were quite robust, as the high temperature heat exchangers and reactor vessels were made of Inconel. The design was well-integrated, especially with respect to heat recovery from the reactors and flow streams, as the majority of the heat released was recovered for preheating reactant feed stocks. During operation, the unit operated in a very stable fashion, and no evidence of coking was experienced, even during a 30-hour run.

One of the major advantages of the Dais reformer is its ability to operate with fuels containing substantial sulfur contents. This is due to the sulfur tolerant catalyst in the autothermal reactor. However, the water-gas shift reaction catalyst is sensitive to the presence of sulfur, so that sulfur still must be removed before the gas stream reaches that catalyst. However, this can be accomplished by scrubbing the H_2S from the gas stream downstream from the autothermal reactor, a much more convenient point in the process to extract this sulfur.

The goal of our operation of the reformer has been to operate a PEM fuel cell stack on the hydrogen-rich stream provided by the reformer. To date, however, we have been unable to get the gas clean-up stages to work properly, and have not been able to complete this task. We are hoping to accomplish this task in early summer 2001.

In lieu of this experiment, we have attempted to estimate the system performance, from diesel in to the system to AC out. This calculation is necessary to compare the efficiency of the PEM system to that of conventional technology currently in use in remote areas, namely, the diesel electric generator, with an efficiency of about 33% (with today's technology) and rising to close to 40% in the near future.

Our estimates for the autothermal system are as follows: the reformer operates at a conversion efficiency of 80% (Hydrogen energy out to Diesel energy in), 80% of the hydrogen fuel is utilized by the fuel cell, the stack operates at 90% of the pure hydrogen voltage due to the dilution of the gas, the fuel cell efficiency is about 53%, and the inverter efficiency is 90%, giving a resulting efficiency of about 26%. However, there are possibly significant efficiency hits in the system that are not accounted for in this calculation, such as the electrical energy needed to run the blower for the reformer, the possible use of batteries for storage and peaking loads (a necessity in a grid-independent system). These will affect the system efficiency in a negative way. At this point in time, it seems likely that the system efficiency based on current technology will be somewhere in the low 20's.

There are also significant open issues with regards to the PEM stack, especially with regards to stack lifetime. While the industry has projected costs based on stack lifetimes of 40,000 hours, the best results so far are only at 10,000 hours for some single-cell experiments, and a lifetime of only several thousand hours for stacks. While these numbers may be adequate for transportation applications or backup power, they are inadequate for residential power systems, where the fuel cell must operate continuously.

Conclusions

Despite the considerable excitement with regards to PEM residential power systems for distributed generation, evaluation of hardware delivered to the RAPP program indicates that this technology in its present state of development does not present clear advantages for power generation in remote areas. Efficiencies measured are lower than those of conventional power systems, and significant reliability issues remain to be solved. Diesel reforming remains a difficult issue, although the autothermal reformer may be more suited to this fuel than steam reforming. While cost projections based on mass manufacturing indicate that this technology may be economically viable in the future, current prices for PEM systems remain high.

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