An Integrated Fuel Processor For PEM Fuel Cells

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Introduction

Proton-exchange membrane fuel cells (PEMFCs) are of interest for many applications including transportation, commercial vehicles, residential and commercial power generation, emergency power supply, and small portable power supplies. In some cases, commercial utility can be realized by supplying hydrogen to the PEMFC stacks from a cylinder of compressed gas. However, for many applications, economic feasibility depends on the successful development of a practical and low-cost fuel processor. Despite extensive efforts to develop partial oxidation (POX) and autothermal reforming for this application (Kumar et al, 1996; and Recupero et al, 1996), these fuel processing methods have not proven to be entirely satisfactory and a new approach is needed.

Northwest Power Systems (NPS) is developing a family of versatile fuel processors based on a novel design that combines steam reforming with hydrogen purification. The resulting integrated fuel processor promises to be affordable, highly compact, and lightweight. Moreover, the NPS fuel processor offers advantages over alternative conventional processes including POX, autothermal reforming, and steam reforming.

Objective

The goal of this program is to design, build, and test a prototype fuel processor that meets the following requirements:

1. capable of recovering 70% to 80% of the available hydrogen;
2. good load-following characteristics;
3. capable of delivering hydrogen containing <10 ppm CO; and
4 low cost.

Furthermore, it is preferable that the fuel processor be compact in size and lightweight. High-purity product hydrogen from the fuel processor (>99% pure) will allow the fuel cell stack to deliver the highest possible power density for a given set of operating conditions (Inbody et al, 1996).

Approach

To achieve these goals, NPS has completed the design of an integrated fuel processor that combines steam reforming, heat production, and hydrogen purification into a single device. The key features of the integrated fuel processor are shown in Figure 1. High-pressure steam reforming, rather than POX or autothermal reforming, is used for the production of hydrogen from a feedstock for the following reasons:

1. hydrogen yields are significantly greater;
2. hydrogen purification is more readily accomplished since POX and autothermal reforming are relatively low pressure operations that result in significant dilution of the product hydrogen by nitrogen (from air); and
3. overall energy efficiencies typically are highest for steam reforming.

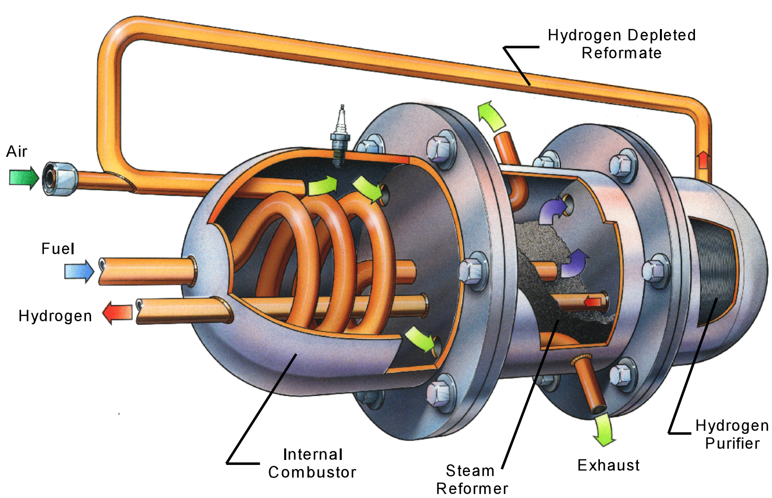

Figure 1. Cut away view of the NPS integrated fuel processor.

Steam reforming is conducted at elevated pressures (about 100 psig to 250 psig) using commercial catalysts and temperatures in the range of 300ºC to 600ºC. The reformate stream is purified using a two-stage purifier that also operates within the same temperature range, allowing direct integration of the reformer and purifier without the need for intermediate heat exchange. The first stage of the purifier performs a bulk separation of hydrogen from reformate and consists of a hydrogen-permeable metal membrane. The second stage of the purifier serves to reduce the CO and CO_2 content of the hydrogen to very low levels. Thus, the product hydrogen is >99% pure and contains <10 ppm CO and <50 ppm CO_2.

A unique feature of the NPS integrated fuel processor is that the two-stage hydrogen purifier is minimized in size and cost by limiting hydrogen recovery to only 70% to 80% of the hydrogen generated by steam reforming. The balance of the hydrogen, along with other byproduct gases and unreacted feedstock, is then conveniently used as a gaseous fuel to provide the required heat for (a) vaporizing the liquid feedstock and water, (b) heating the vaporized feedstock to the reforming temperature, and (c) providing heat to the catalytic reforming bed to satisfy the steam-reforming reaction enthalpy. This approach eliminates the requirement for an external burner fired with unreacted feedstock. The net result is high overall conversion to hydrogen at a reduced cost.

Results

The technical feasibility of this integrated fuel processor has been demonstrated at the bench scale by generating 2.5 L/min of product hydrogen. The product hydrogen was >99% pure and contained no detectable CO and CO_2 (<2 ppm CO and <2 ppm CO_2 given the limits of detection). With this bench-scale prototype fuel processor we have demonstrated overall energy efficiencies (using methanol/water mix as the feedstock) of 70% to 75% (HHV). Efforts are presently underway to scale up the fuel processor to deliver 50 L/min product hydrogen, sufficient for a nominal 5 kW PEMFC stack.

It has been necessary to iterate the design of the combustor and hydrogen purifier as part of the scale-up effort. In particular, the design of the combustor has been improved with respect to heat transfer and low pressure drop. The previous generation of combustor utilized a long tube arranged as a spiral and placed within the catalytic reforming bed. However, this design suffered from moderately high pressure drop and large (about 100ºC to 200ºC) temperature gradients. We now favor a new design as shown in Figure 1 in which a combustion chamber vaporizes and superheats the feedstock and then exhausts through one or more straight tubes that pass through the reforming catalyst bed.

The two-stage hydrogen purifier is currently being designed as a compact brazed-plate module. Previously we were utilizing a tubular design, but this proved to be too bulky.

Steam reforming must be conducted at pressure to provide the driving force necessary for hydrogen separation using the first stage (membrane) of the purifier. Figure 2 shows the relationship between the reforming pressure and the required membrane area. Since the membrane is composed of an alloy of palladium, it is important to minimize membrane area to achieve acceptable costs.

There is reduced benefit to operating the reforming reactions at pressure much greater than about 250 psig, and the parasitic power load for pumping the liquid feedstock to this pressure is insignificant. Therefore, this is the target operating pressure for the fuel processor. Fortunately, nearly all commercial feedstocks are available as liquids, including methanol, ethanol, propane, gasoline, diesel, and jet fuel. The only commonly used feedstock that is not readily available as a liquid is natural gas. So, for natural gas the optimum reforming pressure is likely to be much less than 250 psig, perhaps about 100 psig, although an optimized system design for natural gas has not been completed.

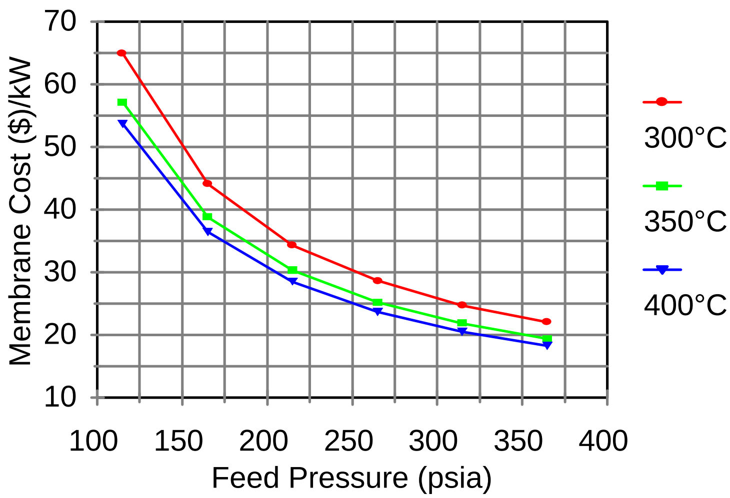

Figure 2. Required area of palladium-alloy membrane as a function of the reforming pressure and operating temperature. Basis: 65% hydrogen in reformate, 75% hydrogen recovery, product hydrogen at ambient pressure.

Applications and Benefits

Obviously, it is important to evaluate more than just the technical merits of a potential fuel processor for use in PEMFC systems--the economics of the fuel processor must also be compared and contrasted to the economics of other fuel processor options. More to the point, the economics of the entire fuel cell system should be evaluated to determine the impact of the choice of fuel processor on the capital and operating costs to the end user. In this type of analysis the NPS integrated fuel processor shows significantly lower capital and operating costs in comparison to other conventional fuel processing methods. For example, Table I qualitatively compares and contrasts the NPS integrated fuel processor and a typical POX reactor using methanol as the feedstock (similar results are obtained when this evaluation is conducted using propane, ethanol, or other feedstocks in place of methanol).

Table I. Characteristics affecting the economics of the NPS integrated fuel processor and a typical POX reactor, both operating on methanol.

Characteristic	**NPS Integrated Fuel Processor**	**POX Reactor**
Process	Steam Reforming	Partial Oxidation in Air
H_2 Concentration in Reformate	65% to 75%	30% to 35%
Subsequent Purification Operations	None Required	Low Temperature WGS, Selective CO Oxidation
Product H_2 Purity	>99%	40%
Moles H_2 Produced/Mole Methanol Consumed	3	2
H_2 Recovery	>70%	100%
H_2 Utilization	98%	60%

The primary difference between the operation of the NPS integrated fuel processor and the operation of a POX reactor is in the purity of hydrogen produced by each method. As shown in Table I, the purity of hydrogen produced by the NPS fuel processor is very high, whereas the POX reactor cannot deliver high purity hydrogen. The low cost of the POX reactor, an often stated advantage, is offset by the requirement of subsequent purification steps (WGS reactor and selective oxidation) and heat exchangers. The requirement for these subsequent operations also makes the POX reactor considerably larger, heavier, and more complex than the NPS fuel processor.

An improvement to POX is autothermal reforming, in which a reforming catalyst is placed within the reactor and supplemental water is injected to achieve slightly higher hydrogen concentrations in the product stream. However, while this approach raises the hydrogen content from about 40% to 50% (Kumar et al, 1996), it has the disadvantage of increasing the cost and complexity of the system by requiring the addition of a catalyst bed and water injection.

Another significant economic advantage of the NPS integrated fuel processor is that it has a high yield of hydrogen per unit of feedstock consumed. This results from the use of water as the oxidant--water contains chemically bound hydrogen that is released as product hydrogen during the steam reforming process.

Now, turning our attention to the integration of these two fuel processing methods into a standard PEMFC system rated to deliver nominally 5 kW, we see another economically significant difference between the two approaches. Specifically, the low purity hydrogen delivered by the POX reactor yields (a) relatively low power output from the PEMFC stack, and (b) low utilization of the hydrogen fed to the stack. The low power output from the fuel cell stack is caused by both the low hydrogen partial pressure (given a fixed total anode gas pressure) and mass transfer resistance that appears as hydrogen is consumed at the anode. Since the hydrogen partial pressure continues to decrease as hydrogen is consumed, and mass transfer resistance continues to increase, the net result is relatively low hydrogen utilization. This problem is manifested in the form of an increased system cost (since the fuel cell stack must be increased in size in the case of POX) and increased feedstock utilization rate. These results are summarized in Table II.

The analysis in Table II leads us to conclude that the NPS fuel processor will lead to lower overall operating costs due to a higher energy efficiency, which in turn results from higher purity of hydrogen delivered to the PEMFC stack. However, it is also expected, based on this analysis, that the capital cost of a PEMFC system using the NPS integrated fuel processor will be less than that for a system using POX or related fuel processing methods. The difference in capital cost is most directly attributed to the difference in PEMFC stack gross power rating (i.e., stack size). For this analysis, the estimated cost for the system assumes the cost of the stack and all supporting hardware (excluding fuel processor) is $1,500/kW. The NPS fuel processor is projected to cost $400/kW, and the POX reactor with subsequent WGS reactor, selective oxidizer, and heat exchanger, is estimated to cost about $550/kW.

Future Activities

Activities are currently in progress to scale up the integrated fuel processor to 5 kW. A prototype 5 kW fuel processor is anticipated by the end of the year. Since the integrated fuel processor can utilize a range of different feedstocks in addition to methanol, NPS is also directing a portion of its effort at producing hydrogen from propane and other selected feedstocks with the goal of demonstrating, during 1998, a family of fuel processors operating on a range of feedstocks.

Table II. Performance and economic comparison of two 5 kW (net) PEMFC systems based on the NPS fuel processor and a POX reactor, assuming methanol is the feedstock.

Parameter	**NPS Integrated Fuel Processor**	**POX Reactor**
PEMFC Gross Power	5.85 kW	7.25 kW
Parasitic Load (Total)	about 17%	about 16%
H_2 Utilization	98%	60%
Feedstock Efficiency (@ 0.6V/cell)	0.128 Gal. Methanol/kW (Gross)	0.219 Gal. Methanol/kW (Gross)
Feedstock Consumption Rate (5 kW Net)	0.75 Gal. Methanol/Hr.	1.6 Gal. Methanol/Hr.
System Cost (Est.)	$11,000	$15,000

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