V.F.5 Cost-Effective, High-Efficiency, Advanced Reforming Module

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Objectives

Develop an advanced reforming module for stationary applications

- Develop a 1,000 scfh (2.4 kg/hr) fuel processor with low product life cycle cost. Minimize capital, operating and maintenance costs over a 40,000-hour life.
- Develop a scaleable technology from 500 to 2,000 scfh (1.2 to 4.7 kg/hr).
- Achieve a cost-effective balance between efficiency and durability.
- Demonstrate a lifetime assessment through accelerated aging.
- Validate performance of a 1,000 scfh fuel processor at Argonne National Laboratory (ANL).

Technical Barriers

This project addresses the following technical barriers to developing a natural gas or LPG fueled fuel processing system from the Fuel Cells section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan [1].

(A) Durability
(B) Cost
(I) Hydrogen Purification/Carbon Monoxide Cleanup
(J) Startup Time/Transient Operation

Technical Targets

Status versus the DOE technical targets for fuel processors [1] is presented in Table 1.

TABLE 1. Nuvera Progress Toward Meeting DOE Stationary Fuel Processor Targets

Characteristic	Units	2005 Target	2010 Target	Nuvera Status
Cost[1] (Small <325 kW)	$/kWe	500	250	506
Durability (catalyst and major component lifetime)	hours	16,000	40,000	40,000
Survivability	°C	-30/+40	-35/+40	-20/+40
CO content in product stream	ppm			
– Steady state		5	1	0.2
– Transient		50	25	<6
H_2S content in product stream	ppm	<5	<2	<0.01

[1] Cost includes entire generation and purification system. Cost of goods sold includes materials, assembly, freight and warranties and assumes 2,000 units/year. The kWe conversion assumes 53% Nuvera fuel cell efficiency.

Accomplishments

- Completed a rigorous design review of the fuel processor sub-system to include a detailed document package consisting of 119 released drawings.
- Fuel processor designed to achieve a durability of 40,000 hours and 1,000 cycles.
- Selected Inconel-625 as the reformer material to provide the lowest life cycle cost after considering capital, operation, and maintenance costs over the 40,000 hour lifetime.
- Achieved hydrogen purity (>99.995% H_2, CO <0.5 ppm) when integrated with a pressure swing adsorber (PSA).

Introduction

Over the past several years, Nuvera Fuel Cells has developed steam reformer technology for incorporation into several stationary fuel cell power systems. Technology assessments have indicated that significant cost reductions and durability improvements are required in order to make the commercialization of stationary fuel cell systems a reality. Previous research in developing steam reforming technology has sought to maximize efficiency by integrating the reformer, burner, steam generator, super heater and water-gas-shift reactor into a single vessel. While the end result was a highly efficient fuel processor, it was not very well suited for manufacturability, durability, serviceability or low cost. In order for a small-scale steam reforming technology to be ready for commercialization, it is imperative that these remaining parameters be adequately addressed.

Approach

The intent of this project is to develop a modular steam reformer while striking an appropriate balance between cost, efficiency, durability and manufacturability. A low pressure steam reformer will be produced to address the widest range of applications with the lowest risk. The reformer will be designed for high efficiency and long life, low capital cost in accord with design for manufacturing and assembly (DFM&A) principles, and will respect strict emissions standards. The intent is to develop a steam reformer technology that is scaleable to produce from 500 to 2,000 scfh of hydrogen. A 1,000 scfh steam reformer will be validated at ANL. Lifetime confidence will be achieved through a combination of endurance testing and thermal profiling studies. The cost structure will be modeled after DOE's H2A forecourt model for steam methane reformers [2].

Due to the complex interactions between the fuel processor sub-system and the un-utilized exhaust from the fuel cell or hydrogen purification sub-system, it is necessary to optimize the design and operation of the fuel processor in a system level context. Nuvera's first application for this fuel processor technology will be in a distributed hydrogen generation and refueling station for fuel cell vehicles. In this application, the burner must be able to startup on natural gas, transition to reformate (syngas) while the PSA is pressurizing, and then run off of the PSA raffinate (un-utilized exhaust) and supplemental natural gas during steady-state operation. The burner must also be able to tolerate pulsations in mass and compositional flow from the PSA without impacting the steam reformer efficiency.

The most significant stigma associated with small-scale reformers is durability. While industrial-scale reformers have been in use for decades, they rarely see more than a single thermal cycle per month. In order for a small-scale reformer to survive daily thermal cycles, the stresses must be reduced to exceptionally low levels. This can be achieved by utilizing a low-pressure reforming process, a free-hanging reformer tube design, minimizing peak metal temperatures, and proper material selection.

Results

The fuel processor design philosophy incorporated the functional requirements, design of the reforming process, inputs from computational fluid dynamics (CFD) modeling and DFM&A principles to influence the mechanical design, a stress and failure mode analysis, material selection, and a life-cycle cost analysis to arrive at the final detailed design.

Functional Requirements

The customer driven functional requirements of the fuel processor are detailed in Table 2.

Reforming Process Design

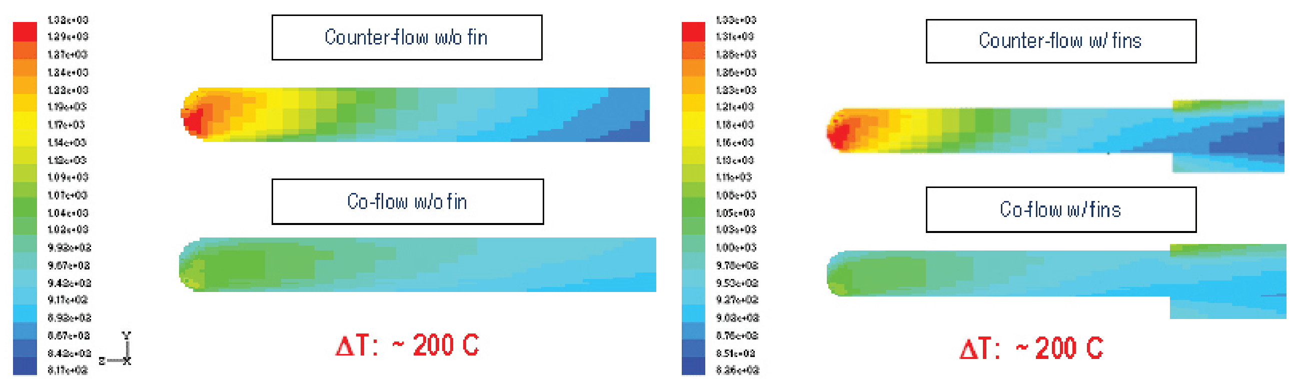
The Fuel Processor 1 (FP1) series architecture consists of 12 hanging steam reformer tubes blanketed by an up-flow exhaust draft burner. This design affords simple plumbing reconfigurations to assess both counter-flow and co-flow modes of operation. The process design envelope was assessed for both operating modes, with respect to the fuel processor efficiency, operating costs, percent methane slip (un-reformed natural gas), and supplemental fuel required to the burner. A heat transfer/reaction model was developed to consider the combustion of the PSA raffinate mixture (H_2, CO, CH_4) and the steam reforming of CH_4. The peak metal temperatures in the baseline counter-flow operation were about 1,050°C at the impingement of the burner flames on the reformer tube caps. Peak temperatures were by reduced by about 200°C with a co-flow operation, where the reformer tube/cap area is quenched by the cooler natural gas and steam mixture. The reduced efficiency of a co-flow operation was partially off-set by adding fins on the outside of the reformer tubes for improved heat transfer (Figure 1).

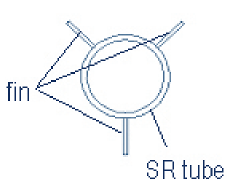
Mechanical Design

The fuel processor consists of three main assemblies: outer shell, steam reformer core and inner core modules. The outer shell includes an air jacket and internal insulation to minimize heat loss. In order to reduce maintenance costs, the fuel processor was designed to facilitate a field replacement of the steam reformer core module. Extensive use of CFD modeling was employed in the design of the burner fuel distribution manifold, the burner fuel/air pre-mixing chamber, the steam

TABLE 2. Fuel Processor Functional Requirements

Characteristic	Design Basis	Comments
Fuel Supply	Grid Supplied, regulated US Natural Gases: Natural Gas: 17-35 mbar (7-14" W.C.)	GEN1-GA = US NG Only GEN2-GA = US/EU/JP NG
Maximum Fuel Capacity	125 kWth input (LHV, NG) in SR 65 kWth input (LHV, mixed fuel) in Burner	Provides for 115% Safety Factor Defined for US NG Operation Only
H2 Generation Rate Reformer H2 Efficiency	75.5 kg/day (Incl. WGS) pre PSA Baseline target = 94% Defined: H2 to PSA (LHV)/Total NG Fuel (LHV)	At 75% PSA Recovery = 56.6 kg/day (1,000 scfh) Product H2 Defined for Cambridge US NG Only
SR Operating Pressure	≤2.7 bar	Assumes use of Reformate Compressor
Cost of Goods Sold & Operating Cost	COGS <$40,000 @ QTY = 50 Operating costs <$1.30/kg (Forecourt production)	COGS: capital, assembly, warranties, margin Assumes $6.00/MMBTU NG cost
Design Life	40,000 hours Target	90% FP's to exceed target Predicated on SR Catalyst Lifetime of 40k
Maintenance Interval	4,000 hours maintenance interval	Related Primarily to Desulfurizer & filters
Maximum Cold Start Cycles	250 Cycles over Design Life	Assumes 1 Cold Cycle per week
Operating Mode	Single Output, On/Off Operation 3 Burner Modes: NG, Reformate, NG/Raffinate	SS Output = 56.6 kg H2/day (1,000 scfh) SS & Idle Operation Modes
Steady State Emissions	<15 ppmv NOx (@ 3% O2, 3 hr average) <30 ppmv CO (@ 3% O2, 3 hr average)	NOx = SCAQMD Requirements CO = BACT Requirements
Safety	CSA FC1, Requirements 5.99, H2 generators ASME B31.3, Process Piping NFPA 52, National FG code	Must meet all applicable Codes & Standards





Study Case	SR Flow Direction	Peak[1] Metal Temp.	Inside Gas Temp. at SR Cap[2]	CH4 Slip (Dry mol%)
No Fin	Counter-flow	~1050 C	~840 C	1.5%
	Co-flow	~850 C	~600 C	4.6%
3 Fins on Burner Side	Counter-flow	~1050 C	~880 C	0.9%
	Co-flow	~850 C	~600 C	4.0%

1. Adiabatic Flame T = 1250C; 2. Corroborated between CFD & Hysys

Co-flow marries the TGC exotherm with the strong SR endotherm

FIGURE 1. Steam Reformer Flow Direction Study with Fins

reformer distribution manifold, the selection of a flame indicator location, and in assessing the effect of assembly tolerances on the reformer performance.

Stress & Failure Mode Analysis

Low pressure reforming and small diameter reforming tubes result in a low hoop stress design (< 300 psi). There are four failure modes known to affect the durability of the steam reformer: creep, low-cycle fatigue, corrosion, and a creep-corrosion interaction. Creep is a long-term concern at the point where the burner flames impinge upon the reformer tubes. Low-cycle fatigue results from a large temperature gradient associated with each on/off cycle of the reformer. Corrosion is a concern in the oxidizing environment of the burner side of the reformer tubes. A creep-fatigue interaction is believed to be the most critical failure mode whereby creep can promote the initiation of small cracks which can then propagate rapidly under cyclic fatigue. Weld locations are also particularly susceptible to high temperature failures as microstructural differences between the weld and base material can result in a stress concentrator. A rigorous failure mode effects analysis was conducted to assess the likelihood of occurrence, and detectability and severity of each failure mode. Areas with high risk priority numbers were creep-fatigue in the steam reformer tubes, catalyst deactivation in < 40,000 hours, and failure of the steam generators.

Material Selection

In order to achieve the 40,000 design life, a very low-stress design and low peak metal temperatures are essential. Several materials were considered for the steam reformer tubes including 310 SS, HK-40, Inconel 600 and Inconel 625 (cost increases from first to last). The selection process sought to balance the resistance to creep, low-cycle fatigue, and corrosion with the required material thickness and cost. While it is possible to select a material to provide adequate protection against these failure modes, there was insufficient published data to design for the creep-fatigue interaction.

Life Cycle Cost Estimation

Rather than optimize the fuel processor design based on the capital cost alone, a life cycle cost assessment was conducted to include the estimated operating and maintenance costs over the 40,000 target lifetime. Due to slightly lower efficiency, the co-flow operation cost was determined to be $0.05/kg higher than for counter-flow. Capital costs included direct materials, assembly, freight, warranties and gross margins. Based on peak metal temperatures and material properties, a durability assessment was made to estimate the number of reformer core replacements per 40,000 hours. The maintenance costs considered the materials, labor and freight for each reformer core replacement. After considering the various material and operational mode options, it was determined that an Inconel-625 reformer core with a co-flow operation had the lowest life cycle cost.

Conclusions and Future Directions

With a low-stress reformer design, a co-flow operational mode to reduce peak metal temperatures, and selection of Inconel-625 for the reformer core materials, it is expected that the fuel processor can withstand 40,000 hours of operation and 1,000 cycles. In the absence of creep-fatigue interaction data, a very conservative approach was made by selecting the more resistant Inconel-625 until such data can be generated. Nest steps:

- Accelerated aging trials have commenced, cycling the burner and flame impingement on the reformer tubes to simulate the maximum thermal stress under 500 rapid cycles.
- Conduct a designed experiment with 310 SS, Inconel-625 and 600 tubes under rapid burner cycling to generate creep-fatigue interaction data.
- Assess performance of the new fuel processor design (Inconel-625, fins, co-flow) in a system level context.
- Address potential failure modes with the steam generators and catalyst deactivation.
- Complete a DFM&A assessment of the fuel processor design.
- Commercialize the fuel processor in a hydrogen generation and refueling station.

FY 2006 Publications/Presentations

1. Program review with DOE Technology Development Manager and ANL, 09 Nov. 2005.
2. Presentation to DOE Hydrogen Production group, 07 Mar. 2006.
3. Report: "PowerTap cost analysis using DOE H2A model", submitted to DOE Hydrogen Production group, 19 Mar. 2006.

References

1. HFCIT Multi-Year RD&D Plan, http://www.eere.energy.gov/hydrogenandfuelcells/mypp/.
2. H2A Forecourt Hydrogen Production Model Users Guide, Version 1.0.10, Jul'05, http://www.hydrogen.energy.gov/h2a_production.html.