Compact Microchannel Fuel Vaporizer for Automotive Applications

Jennifer L. Zilka-Marco, Anna Lee Y. Tonkovich,(a) Michael J. LaMont, Sean P. Fitzgerald,
David P. VanderWiel, Yong Wang, Robert S. Wegeng

Pacific Northwest National Laboratory, Battelle Boulevard, Richland, WA 99352

Abstract

The Compact Microchannel Fuel Vaporizer (CMFV), an R&D 100 Award winner in 1999, is a breakthrough in miniaturizing process technology and a key component of a microchannel fuel processor that will enable fuel cell-powered vehicles. Fuel cells, which run on hydrogen, are a high-efficiency, low-emission alternative to the internal combustion engine. No infrastructure now exists to deliver either gaseous or liquid hydrogen to fuel cell-powered automobiles, but a gasoline-distribution infrastructure does exist. The CMFV can vaporize the requisite amount of gasoline needed to power a 50-kWe fuel cell and is small enough (0.3 L) for portable or automotive applications.

Introduction

Fuel cells are recognized as a clean, efficient alternative to the internal combustion engine for automobiles. However, a fuel cell requires hydrogen as its fuel. Currently, no infrastructure exists to deliver either gaseous or liquid hydrogen to fuel cell-powered automobiles, but a gasoline-distribution infrastructure does exist. The challenge in implementing the fuel processing technology needed to convert liquid fuels such as gasoline to hydrogen is reducing the volume and cost of the existing fuel processing hardware. This paper discusses a novel approach for miniaturizing fuel processing technology that reduces the hardware volume by an order of magnitude over conventional technology. The result is a compact, inexpensive, and easy-to-manufacture product that will enable the fuel cell-powered vehicle.

Consumers and society will realize environmentally benign benefits from the widespread use of fuel cell-powered vehicles. Automobiles represent approximately 31% of all CO_2 emissions in the United States (Energy Information Administration 1995). More than a 50% reduction in CO_2 emissions per mile traveled can be achieved by replacing internal combustion (IC) engines with fuel-cell systems. This is because fuel cell systems have an overall efficiency near 45%, while the IC engine operates near 20%.

The Compact Microchannel Fuel Vaporizer (CMFV) is one step within a series of process steps necessary to convert the liquid hydrocarbon fuel to hydrogen. These steps include fuel vaporization, primary conversion of the fuel to synthesis gas, the water-gas shift reaction, and carbon monoxide removal. The CMFV developed at Pacific Northwest National Laboratory has a hardware volume equivalent to a soda pop can, weighs only 4 lb, and can support a 50-kW_e fuel-cell power system.

(a) Author to whom all correspondence should be addressed (ay.tonkovich@pnl.gov).

Background

Fuel cell-powered mobile applications have gained considerable interest over the past 40 years. The initial breakthrough came in the 1960s with the U.S. space program's decision to use fuel-cell power for the Gemini and Apollo spacecraft. Today fuel cells still provide electricity for the space shuttle. Development efforts now are focused on bringing fuel-cell power back to mobile applications on earth. By far the largest investment has been made by the automotive industry, including the "Big Three" automakers, the Partnership for a New Generation of Vehicles, and several small, independent fuel-cell companies. Other mobile applications of interest include fuel cell-powered golf carts, utility vehicles, wheelchairs, bicycles, and marine transportation.

Society's current energy dependence surpasses that of the 1970s and continues to increase. Meeting this demand will undoubtedly require a careful balance of oil supplies, greenhouse gas emissions, and technological innovations. Automotive fuel-cell technology developments promise to create the symbiotic relationship needed between the environment and the economy. Greenhouse gas emissions will be dramatically reduced by millions of tons per year if only 10% of the automobiles nationwide are powered by fuel cells (DOE 1999). The U.S. Department of Energy (DOE) projects that this will translate into a 13% reduction in total imports, thus reducing trade deficits. Furthermore, fuel cells have the potential to generate tens of thousands of high-quality jobs through the creation of new markets for the steel, electronic, and control industries.

Fuel cells require a hydrogen fuel source to create energy in the form of electricity. The hydrogen fuel can be supplied via on-board hydrogen tanks or on-board processing of hydrocarbon fuels. The former approach has been reported by Ford Motor Company (Ford 1997) to be safer than the latter approach when using gasoline, especially if improved hydrogen storage tanks are deployed. For either scenario, the need for small-scale fuel processing systems is crucial for the commercialization of the fuel cell-powered vehicle. On-board hydrogen tanks will require hydrogen refueling stations. Compared with microtechnology, conventional technology has many drawbacks associated with its use at these stations, including massive hardware volumes, high system costs, and the hazards associated with large quantities of stored energy within the fuel processing system. Deployment of on-board automotive fuel processing systems is the alternative to on-board hydrogen tanks and will also benefit from compact microchannel fuel processing. Improvements to the gasoline-powered vehicles could make this option more attractive from a safety perspective.

Processing of hydrocarbon fuels for automotive applications is not an economical option with conventional technology; therefore, innovative developments are needed to make the fuel cell-powered vehicle a reality. In addition to size, the new technology must be efficient and lightweight, and it must accommodate the stringent stream composition requirements of a PEM fuel cell. PEM fuel cells have the capability to handle transients and therefore are the most promising type of fuel cell for automotive applications. However, CO levels above 10 ppm can poison a PEM fuel cell.

To be cost-effective, the system must be able to achieve economy of scale and use the existing gasoline infrastructure. A liquid fuel source such as gasoline requires multiple steps for processing. This multistep process is shown schematically in Figure 1. For liquid fuels, such as gasoline or methanol the first step is vaporization. The vaporized fuel then enters the next stage, which is primary conversion of the fuel to synthesis gas, a mixture of carbon monoxide and hydrogen. Primary conversion is achieved through partial oxidation, steam reforming, or autothermal reforming. The CO is further converted in the secondary conversion reactor (water gas shift reactor), increasing the overall hydrogen concentration of the stream. The final step is CO cleanup via preferential oxidation, which is essential to reduce CO levels below the 10 ppm level requirements of a PEM fuel cell.

Innovative strides are being made at PNNL toward the development of fuel processor systems that meet the size and weight constraints that make the fuel cell-powered automobile competitive. The CMFV is one of these breakthroughs. Weighing only 4 lb and contained within a hardware volume equivalent to that of a soda can, the CMFV is the first small-scale development of its kind. The CMFV uses otherwise wasted fuel from the fuel processor-fuel cell system. Fuel cell exhaust is about 8% hydrogen. The CMFV makes efficient use of this waste hydrogen stream by combusting the hydrogen from the fuel cell anode to provide the heat required to vaporize the liquid gasoline. Development efforts at PNNL have proven catalytic combustion of hydrogen to be a reliable heat source for this

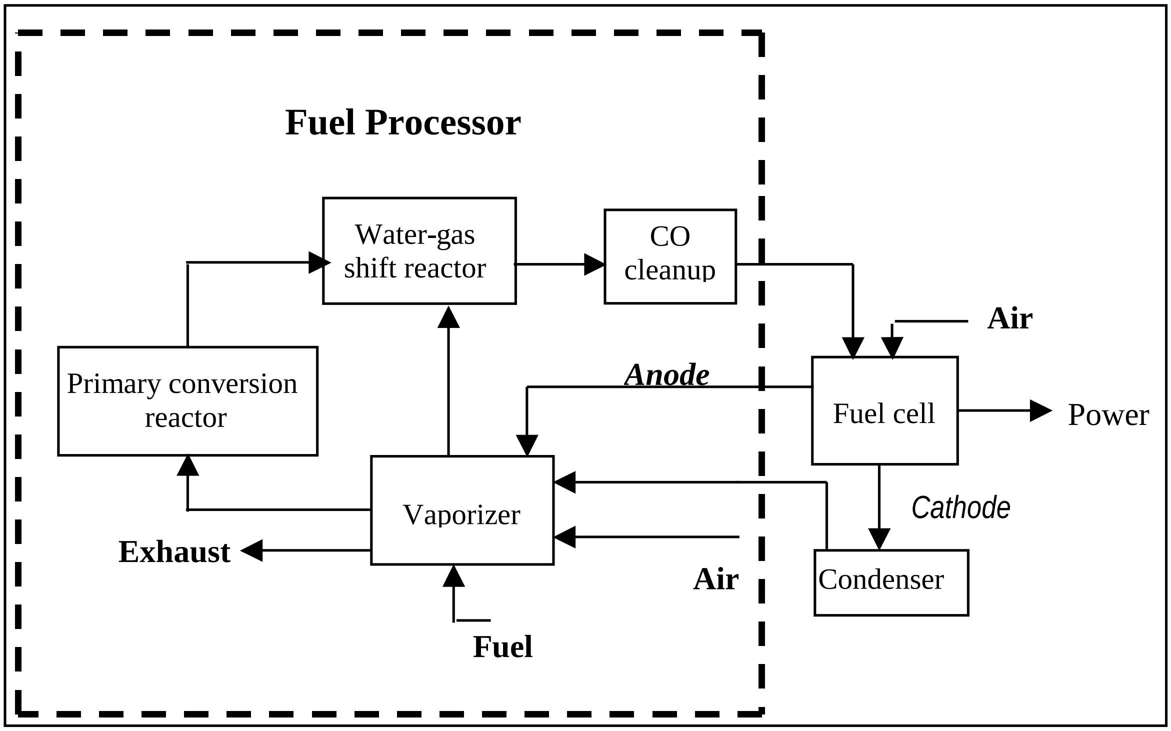

Figure 1. Schematic of Fuel Processor System

application (Tonkovich et al. 1998, 1999). Conventional systems use large pellets of catalysts having numerous microstructures with tortuous dead-end diffusion paths through which molecules must be transported to reach an active catalyst site. In contrast, the CMFV uses an engineered monolithic catalyst featuring small pores through which the gas flows (see Figures 2 and 3). Molecules have to diffuse a distance from 100 to 1000 μm rather than 1,000 to 10,000 μm for pellets.

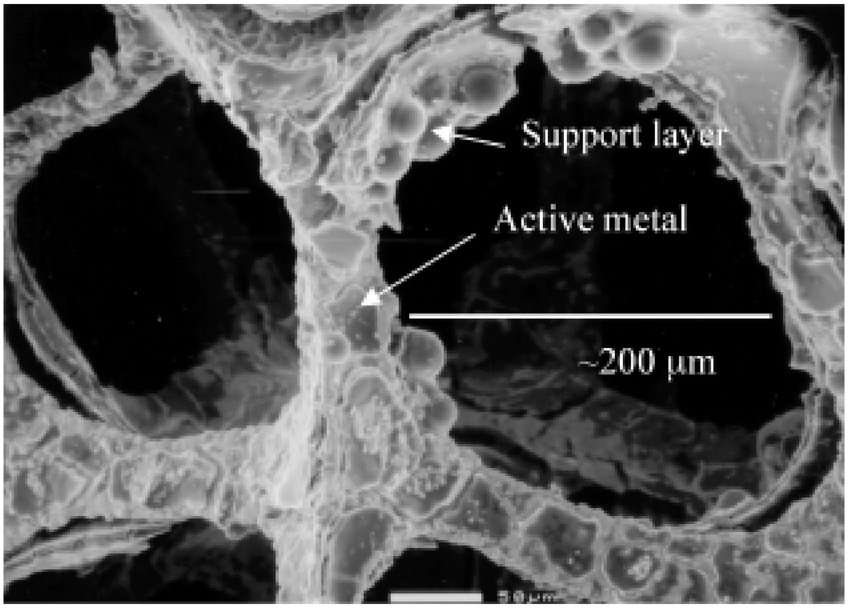

Figure 2. Pore Structure of the Compact Microchannel Fuel Vaporizer's Engineered Catalyst

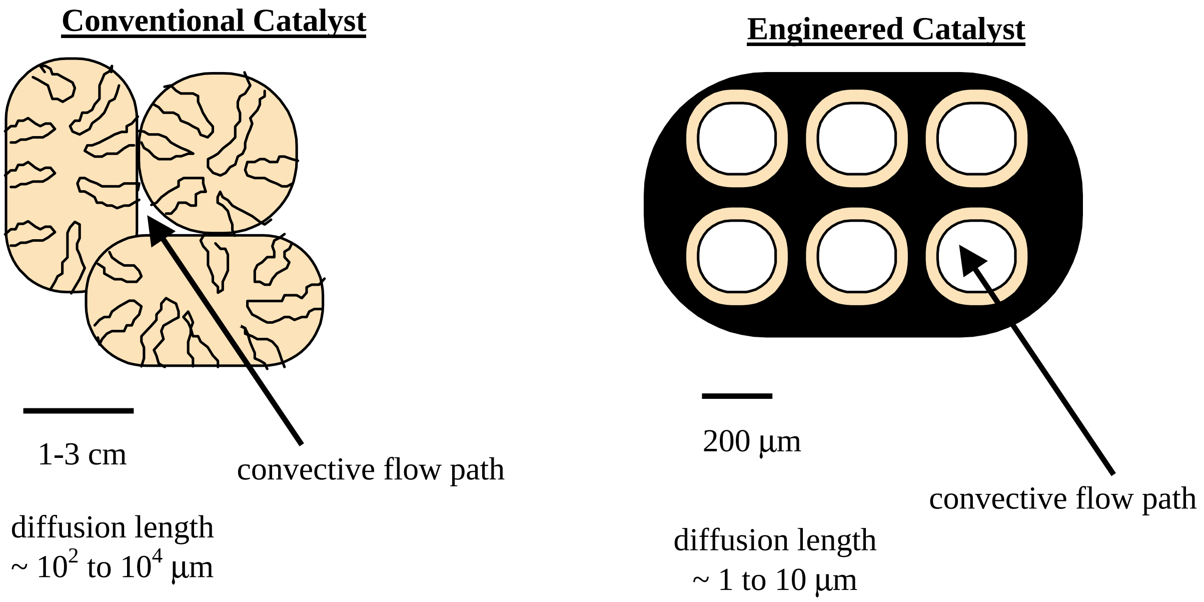

Figure 3. Conventional Versus Engineered Catalysts

The engineered catalysts, when used in conjunction with integral microchannel heat exchangers (Tonkovich et al. 1996; Matson et al. 1998), significantly reduce heat transport limitations that increase the size of conventional technology. This reduction is achieved by using the microchannels to break up a single fluid stream into many parallel small streams, each with a flow width of several hundred microns. These parallel streams are exposed to a larger surface-area-per-unit-volume in the microchannels than a single stream of equal volume passed through a much larger tube (on the order of centimeters) used in a conventional heat exchanger. Therefore, the fluid flowing in the microchannels comes in contact with more hot surface area than a tube of the same volume. In addition, small channels decrease convective heat transfer resistance, improving the effectiveness of the heat exchange surface area so that the heat transfer rate *per unit area* is more than an order of magnitude higher than in conventional heat exchangers. When using a microchannel heat exchanger, the combination of high-surface-area-per-unit-volume design with greatly enhanced heat transfer per unit area allows the heat in the hot combustion stream to be efficiently transferred to the incoming liquid gasoline (see Figure 4).

The simple linear scaling laws of the CMFV add to its flexibility. Additional vaporizer units are simply added in parallel to achieve the desired performance.

A schematic of the CMFV operation is shown in Figure 5. The catalyst sits in a small well (~6.3 mm deep). The combustion gases (or fuel cell anode effluent) enter through the top plate, react in the monolith, and travel down through a hole in the footer to the header of the heat exchanger plate below. The heat exchanger section has back-to-back microchannels. As the hot combustion product gases flow through the microchannels, heat is conducted to the microchannels on the backside, which has countercurrent gasoline flow.

Technology Status

The CMFV has been demonstrated successfully at full scale for a 50-kW_e automotive application. The CMFV's performance was evaluated at partial loads of 25%, 50%, and 100% of expected gasoline flow rates. Under all conditions, complete vaporization of the consumer-grade gasoline was achieved. Testing of variable flue gas feed flow rates to the vaporizer revealed that only 30% of the total expected available anode effluent would be required to vaporize the requisite amount of gasoline for a 50-kW_e system. Compared with conventional and other emerging technologies, the volumetric heat flux capacity of the CMFV developed at PNNL is an order of magnitude larger. Table 1 delineates the many competitive advantages of this technology.

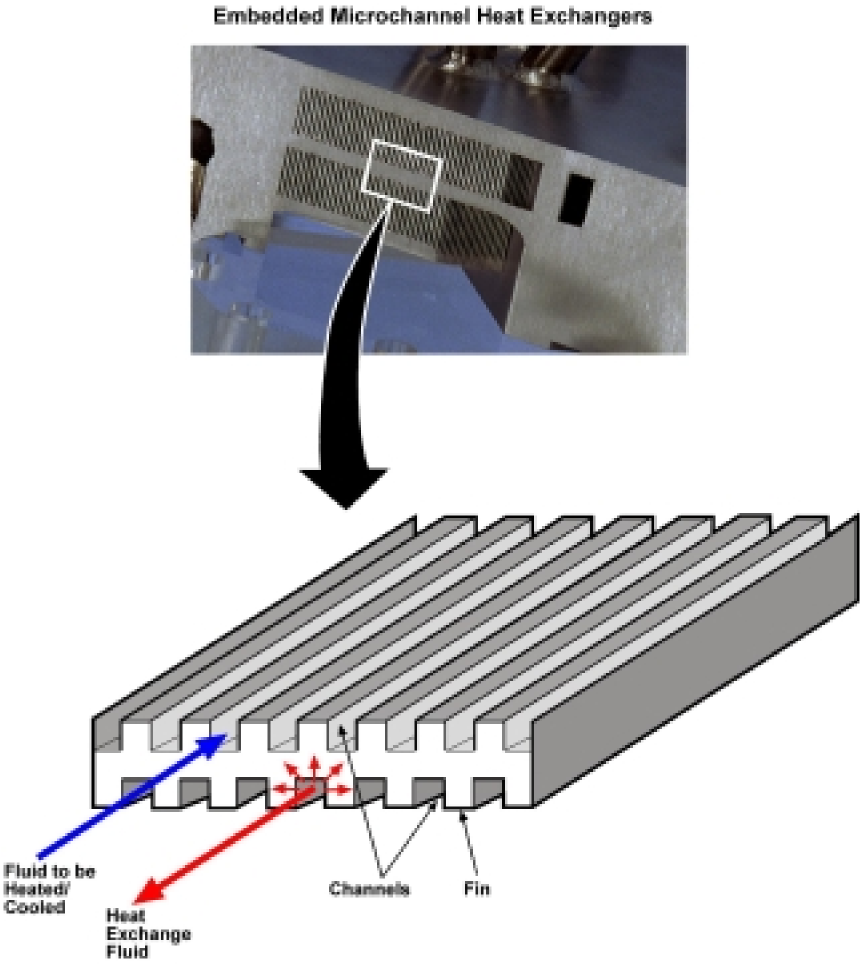

Figure 4. Schematic of Microchannel Heat Exchanger Design

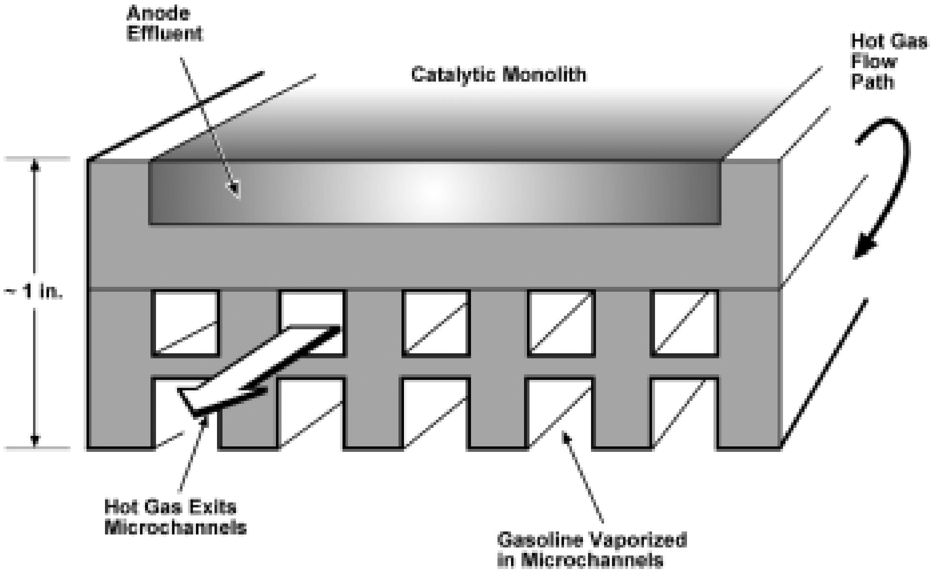

Figure 5. Schematic of Compact Microchannel Fuel Vaporizer Operation

Table 1. Competitive Advantages (Zilka-Marco et al. 1999)

Feature	CMFV	Other Emerging Technologies(a)	Conventional Boiler Technology	Competitive Advantage
Hardware Volume	**0.35 liters**	3 liters	>10 liters	One-tenth the size
Weight	**1.8 kg (4 lb)**	>10 lb	>50 lb	Lightweight—twice as light as nearest competitor; portable
Operation Under Varying Load	**Response time of seconds**	Response time of minutes	Response time of minutes	Responsive to variable automotive load requirements
Heat Flux per Unit Hardware Volume (W/cm^3)	**11.5**	~1.2	0.1 to 1.0	10 times more heat per unit hardware volume
Development Stage	**Demonstrated full-scale(b) device, two units shipped(c)**	Under development	In use	Innovative new technology
Fabrication Method	**Low-cost laminate fabrication**	Conventional extrusion, machining, and welding	Conventional extrusion, machining, and welding	Low labor cost, consistent quality

(a) All work is in the development stage; information is proprietary; estimates are provided where possible.
(b) Supports a 50-kW fuel processor/fuel cell.
(c)The CMFV is currently being integrated within the automotive fuel processor systems under development by two companies.

Acknowledgments

This work was supported by the U.S. DOE EE-Office of Transportation Technology, under the management of Steve Chalk and JoAnn Milliken, who are gratefully acknowledged for their financial and moral support. Pacific Northwest National Laboratory is operated by Battelle for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

References

Energy Information Administration. 1995. *Emissions of Greenhouse Gases in the United States 1987-1994*. DOE/EIA-0573(94), U.S. Department of Energy, Washington, D.C.

Ford Motor Company. May 1997. “Direct-Hydrogen-Fueled Proton-Exchange-Membrane Fuel Cell System for Transportation Applications: Hydrogen Vehicle Safety Report,” pp.17-18.

Matson DW, PM Martin, AY Tonkovich, and GL Roberts. September 1998. “Fabrication of a Stainless Steel Microchannel Microcombustor Using a Lamination Process.” *Proceedings of the SPIE Micromachined Devices and Components IV Symposium*, Vol. 3514. Santa Clara, California.

Tonkovich AY, DM Jimenez, JL Zilka, MJ LaMont, Y Wang, and RS Wegeng. March 1998. “Microchannel Chemical Reactors for Fuel Processing.” *Proceedings of the Second International Conference of Microreaction Technology,* New Orleans.

Tonkovich AY, SP Fitzgerald, JL Zilka, MJ LaMont, Y Wang, DP VanderWiel, and RS Wegeng. March 1999. “Microchannel Chemical Reactors for Fuel Processing Applications. II. Compact Fuel Vaporization.” *Proceedings of the Third International Conference of Microreaction Technology,* Frankfurt, Germany.

Tonkovich AY, CJ Call, DM Jimenez, RS Wegeng, and MK Drost. 1996. "Microchannel Heat Exchangers for Chemical Reactors." *Proceedings of the 1996 National Heat Transfer Conference*, Houston.

U.S. Department of Energy. 1999. "Fuel Cells 2000: Benefits of Fuel Cells." http://216.51.18.233/fcbenefi.html

Zilka-Marco JL, AY Tonkovich, M Powell, GL Roberts, Y Wang, SP Fitzgerald, RS Wegeng, PM Martin, DW Matson, and DC Stewart. February 1999. "Compact Microchannel Fuel Vaporizer." R&D 100 Award Entry, Pacific Northwest National Laboratory, Richland, Washington.